UNIVERSIDADE DO PORTO
FACULDADE DE DESPORTO

CENTRO DE INVESTIGAÇÃO FORMAÇÃO INOVAÇÃO E INTERVENÇÃO EM DESPORTO
CIFI2D

Energetics, kinematics and active drag in the breaststroke swimming technique

Academic thesis submitted with the purpose of obtaining a doctoral degree in Sports Sciences according to the Decree-Law 74/2006 from March 24th

Advisor: Prof. Dr. João Paulo Vilas-Boas

Co-Advisor: Prof. Dr. Tiago M. Barbosa

Miriam Natacha Rodrigues Alves

Porto, 2025

Alves, M. N. (2025). Energetics, kinematics and active drag in the breaststroke swimming technique. Doctoral Thesis in Sport Sciences. Centre of Research, Education, Innovation and Intervention in Sport. Faculty of Sport, University of Porto.

KEY-WORDS: BREATHING PATTERNS; SWIMMING EFFICIENCY; HYDRODYNAMICS; PERFORMANCE; ENERGY COST; BIOMECHANICS

PALAVRAS-CHAVE: PADRÕES RESPIRATÓRIOS; EFICIÊNCIA NA NATAÇÃO; HIDRODINÂMICA; DESEMPENHO; CUSTO ENERGÉTICO; BIOMECÂNICA

Funding

This Doctoral Thesis was supported by the Portuguese Science and Technology Foundation (FCT) grant https://doi.org/10.54499/2021.08308.BD

Acknowledgments

This limited space does not allow me to adequately thank everyone who, in some way, contributed to my academic journey and the development of this Thesis. Therefore, I leave here a few words to express my immense gratitude for all the support I received:

To Professor Dr. João Paulo Vilas-Boas, thank you for giving me the opportunity to be your student. I am deeply grateful for your guidance, availability, support, scientific expertise, and for generously sharing your knowledge throughout my academic path.

To Professor Dr. Tiago M. Barbosa, thank you for your continuous support, scientific insight, and valuable guidance throughout this journey. Your feedback, encouragement, and availability were fundamental to the development of this work.

To Professor Dr. Ricardo Fernandes, I express my gratitude for the trust you placed in me from the very beginning of my academic journey, for always encouraging my curiosity, my drive to deepen my knowledge, and my constant pursuit of improvement.

To the swimmers of *Leixões Sport Club*, a special thank you for your time, commitment, and enthusiasm during data collection, and for all the support you gave me throughout.

To all the collaborators, thank you for your time, dedication, and commitment throughout the data collection processes. Your support and involvement were essential to the successful completion of this research.

To my family, thank you for your unwavering encouragement, trust, and strength that helped me through this phase. I am also grateful for the opportunity to pursue higher education and for the values and support that fostered both my academic and personal development.

To everyone at *Leixões Sport Club*, my second family, my deepest thanks for helping me grow every day, as a person, athlete, coach, and student. “Juntos somos mais fortes”.

Finally, to all those I have not mentioned by name, friends, colleagues, and collaborators, who directly or indirectly contributed to this dissertation, my sincere appreciation.

List of publications

This Doctoral Thesis is based on the following scientific papers:

1. Alves, M., Barbosa, T. M., & Vilas-Boas, J. P. (2024). Variability of energy cost in breaststroke technique: a systematic review. *Sports biomechanics*, 1-41. https://doi.org/10.1080/14763141.2024.2427683.

2. Alves, M., Monteiro, A. S., Fernandes, R. F., Barbosa, T. M., & Vilas-Boas, J. P. (2025). Does breathing every two cycles reduce the breaststroke energy cost? *International journal of sports medicine*. DOI: 10.1055/a-2657-9181

3. Alves, M., Barbosa, T. M., & Vilas-Boas, J. P. (2024). Exploring the impact of breathing patterns on active drag in breaststroke swimming. *Journal of biomechanics*, 112390. https://doi.org/10.1016/j.jbiomech.2024.112390.

4. Alves, M., Fonseca, P., Fernandes, A., Brito, A. V., Barbosa, T. M., & Vilas-Boas, J. P. (2025). Analyzing Breathing Patterns in the Breaststroke Technique Through Dual-Media Kinematics and Fractal Dimension. *Sensors*, *25*(10), 3104. https://doi.org/10.3390/s25103104

5. Alves, M., Fonseca, P., Machado, L., Costa, M., Soares, S., Fernandes, R. F., Barbosa, T. M. & Vilas-Boas, J. P. Determinants of breaststroke performance: the interplay of efficiency, active drag, and energy cost. Submitted to *European journal of applied physiology*.

Table of contents

Index of figures

Index of tables

Index of equations

Abstract

Swimming performance depends largely on energetic demands, which are shaped by swimmers' biomechanical and motor strategies. Breaststroke presents unique biomechanical and physiological characteristics. While breathing patterns have been studied in the butterfly technique and front crawl, their effects in breaststroke remain underexplored, despite the flexibility allowed by World Aquatics rules. The primary objective of this doctoral thesis was to compare and characterize two distinct breathing patterns, breathing every cycle and breathing every two cycles, in the breaststroke technique. Specifically, the research aimed to: (1) analyze and compare these breathing patterns through kinematic parameters of key reference points (hand, foot, head, and center of mass) across different movement planes, and (2) evaluate their effects on energy cost, efficiency, and active drag. Fifteen swimmers underwent a six-week intervention to learn the new breathing pattern. Subsequently, they performed a 5 × 200 m step test (with 0.05 $m \cdot s^{-1}$ increments and 30 seconds rest) under both breathing conditions, two 25 m all-out trials using the velocity perturbation method in each breathing pattern, and three maximal 25 m efforts in each breathing pattern. The results showed that: (i) breathing every two cycles in breaststroke was associated with higher values of key bioenergetic variables, including peak blood lactate concentration, peak oxygen uptake, total metabolic power output, and energy cost, particularly at moderate to high intensities; (ii) inter-individual variability was observed in swimmers' hydrodynamic and energetic responses to different breathing patterns in breaststroke; (iii) differences in kinematics (amplitudes, angles, velocities, fractal dimension, and intracycle variation of velocity) among the breathing patterns were minimal, with no clear superiority of one breathing pattern over the other; (iv) not breathing was associated with reduced vertical and horizontal head movement amplitudes; (v) this pattern also corresponded with the highest vertical foot velocity and greatest center of mass velocity in the swimming direction, suggesting potential biomechanical advantages; (vi) breathing every cycle enhanced hand efficiency and hand stabilization measures; (vii) breathing every two cycles improved feet stabilization and displacement; (viii) greater motor path stabilization was associated with lower energy cost; (ix) foot and total stabilization indices strongly related to foot displacement; and (x) breathing every cycle showed greater medio-lateral hand amplitude and lower minimum center of mass horizontal velocity. In conclusion, while some swimmers benefited from reduced breathing frequency, overall breaststroke technique was not systematically modified by the breathing pattern.

Resumo

O desempenho na natação depende em grande parte das exigências energéticas, que são moldadas pelas estratégias biomecânicas e padrões motores dos nadadores. O nado de bruços apresenta características biomecânicas e fisiológicas únicas. Embora os padrões respiratórios tenham sido estudados na borboleta e no crol, os seus efeitos em bruços permanecem pouco explorados, apesar da flexibilidade permitida pelas regras da *World Aquatics*. O principal objetivo desta tese foi comparar e caracterizar dois padrões respiratórios em bruços: respirar a cada ciclo e a cada dois ciclos. Especificamente, pretendeu-se: (1) analisar e comparar esses padrões por meio de parâmetros cinemáticos de pontos-chave (mão, pé, cabeça e centro de massa) em vários planos de movimento e (2) avaliar seus efeitos no custo energético, eficiência e arrasto ativo. Quinze nadadores realizaram uma intervenção de seis semanas para aprender o novo padrão respiratório. Posteriormente, executaram um teste progressivo de 5 × 200 m (incrementos de 0,05 $m \cdot s^{-1}$ e 30 segundos de descanso), duas repetições máximas de 25 m com o método de perturbação da velocidade e três sprints máximos de 25 m, todos realizados em ambos os padrões respiratórios. Os resultados mostraram que: (i) respirar a cada dois ciclos em bruços esteve associado a valores mais elevados de variáveis bioenergéticas, como pico de lactato, consumo máximo de oxigénio, potência metabólica total e custo energético, especialmente em intensidades moderadas a elevadas; (ii) houve variabilidade individual nas respostas hidrodinâmicas e energéticas aos padrões respiratórios; (iii) as diferenças cinemáticas entre os padrões foram mínimas, sem superioridade clara; (iv) não respirar levou a menores amplitudes verticais e horizontais; (v) este padrão apresentou maior velocidade vertical máxima dos pés e do centro de massa, sugerindo vantagens biomecânicas; (vi) respirar a cada ciclo melhorou a eficiência e estabilização das mãos; (vii) respirar a cada dois ciclos favoreceu a estabilização e deslocamento dos pés; (viii) maior estabilização do percurso motor associou-se a menor custo energético; (ix) os índices de estabilização dos pés correlacionaram-se fortemente com o seu deslocamento; e (x) respirar a cada ciclo teve maior amplitude médio-lateral das mãos e menor velocidade horizontal mínima do centro de massa. Em conclusão, embora alguns nadadores tenham beneficiado da redução da frequência respiratória, a técnica de bruços não foi sistematicamente modificada pelo padrão respiratório.

Abbreviations

$[La]^-$	Blood lactate concentrations
η_d	Total mechanical propulsive efficiency
η_F	Froude efficiency
η_P	Propelling efficiency
C	Energy cost
C_{Da}	Active drag coefficient
D	Hydrodynamic drag
D_a	Active drag
dv	intra-cyclic variation of the center of mass's velocity
$\dot{E}_{tot}$	Energy expenditure
FD	Fractal dimension
PCr	Phosphocreatine
P_{tot}	Total external mechanical power
$\dot{V}O_2$	Oxygen consumption
VPM	Velocity perturbation method
$\dot{W}_d$	Power to overcome drag
$\dot{W}_{ext}$	External power
$\dot{W}_{tot}$	Total mechanical work

Chapter 1. General Introduction

Performance in competitive swimming is defined as the capacity of a swimmer to travel the race distance as fast as possible, achieving their fastest average velocity. Accordingly, a general equation of swimming performance can be written (di Prampero et al., 1974):

$$v = \dot{E} \times \frac{\eta_d}{D} \tag{1}$$

where, v represents velocity, $\dot{E}$ total metabolic power, η_d total mechanical propulsive efficiency and D hydrodynamic drag. This means that performance is strongly underpinned by energetic variables, and these are dependent on the biomechanical behavior and motor strategies adopted by the swimmers (Barbosa et al., 2010). The swimmer's technical ability (i.e., the subject propelling efficiency plus the ability to overcome drag), and the overall efficiency, strongly affect the energy cost (C) at a given velocity (Zamparo, 2006).

C is defined as the amount of energy spent, above resting, to cover one unit of distance (Barbosa et al., 2005; Pendergast et al., 2003). It is often convenient to normalize the C of locomotion to some appropriate body dimension (e.g., body mass) to enable the comparison between subjects (Zamparo et al., 2000). The ratio between C and v yields the energy consumption per unit of time ($\dot{E}$):

$$\dot{E} = \frac{C}{v} \tag{2}$$

where, C is expressed in J/m^{-1}, v in m/s^{-1} and $\dot{E}$ in W (di Prampero, 1986). However, for practical reasons, C is often expressed in mL O_2 m^{-1} and v in m min^{-1}, in which case, $\dot{E}$ will turn out in mL O_2 min^{-1}. $\dot{E}$ can be calculated by the sum of the aerobic $\dot{E}_{Aer}$, anaerobic lactic ($\dot{E}_{AnL}$) and anaerobic alactic ($\dot{E}_{AnAl}$) energy pathway components (di Prampero, 1993; Capelli et al., 1995, 1998; Zamparo et al., 2000). The faster and longer these sources can be elicited, the larger the bioenergetic power and capacity, and likewise the larger the $\dot{E}$ and velocity. Elite swimmers have both greater $\dot{E}$ and less C than recreational swimmers and, for these reasons, the former can reach faster velocities than the latter (Zamparo et al., 2000). Thus, an athlete can improve performance (v) by increasing $\dot{E}$ and/or by decreasing C.

The increase in $\dot{E}$ with velocity reflects the increase in the total mechanical power ($\dot{W}_{tot}$) that the muscles have to provide to sustain the considered velocity. $\dot{W}_{tot}$ can be calculated as the sum of the internal power (power needed to accelerate and decelerate the limbs with respect to the center of mass, $\dot{W}_{int}$) and the external power (power needed to overcome external forces, $\dot{W}_{ext}$). In swimming, $\dot{W}_{ext}$ can be further partitioned into the power to overcome drag ($\dot{W}_d$), that effectively contributes to propulsion, and the work lost in transferring kinetic energy to the water ($\dot{W}_k$) (Toussaint & Truijens, 2005). The partitioning of the efficiencies in human swimming (Figure 1) is based on the flow diagram of the steps of energy conversion in steady state aquatic locomotion proposed by Daniel (1991) (Zamparo et al., 2020): metabolic energy is converted into contractile work, only a fraction of it goes to moving fluid, out of this work, only a fraction goes into useful thrust.

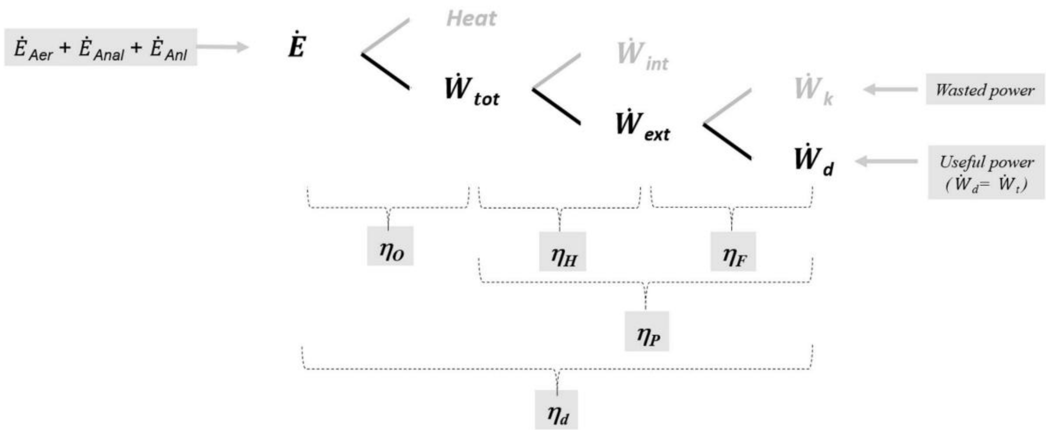


Figure 1- Flow diagram of the steps of energy conversion (Zamparo et al., 2002; adapted from Daniel, 1991). η_d - total mechanical propulsive efficiency; η_o - overall efficiency; η_H - hydraulic efficiency; η_P - propelling efficiency; η_F - Froude efficiency.

Propelling and Froude efficiencies denote the fraction of external and total mechanical power that can be utilized in water to produce useful thrust. The efficiency with which the $\dot{W}_{tot}$ produced by the swimmer is transformed into useful mechanical power (to overcome hydrodynamic resistance, $\dot{W}_d$) is termed propelling efficiency (η_P) (Webb, 1971; Zamparo et al., 2006) and is given by:

$$\eta_P = \frac{\dot{W}_d}{\dot{W}_{tot}} \quad (3)$$

The efficiency with which the $\dot{W}_{ext}$ produced by the swimmer is transformed into useful mechanical power ($\dot{W}_d$) is termed Froude efficiency (η_F) and is given by:

$$\eta_F = \frac{\dot{W}_d}{\dot{W}_{ext}} \tag{4}$$

In human aquatic locomotion, the mechanical efficiency (η_o) (the ratio of total mechanical power, $\dot{W}_{tot}$, to metabolic power, $\dot{\mathrm{E}}_{\mathrm{tot}}$) is lower than the η_P, which is associated with the laws governing the transformation of metabolic energy into mechanical energy in the first stage. Among all swimming techniques, breaststroke showed the greatest η_P values for both male and female swimmers, reaching up to 0.71, while the lowest values were observed in butterfly and front crawl (0.65 for males and 0.67 for females) (Kolmogorov et al., 2021; Toussaint & Truijens, 2005; Toussaint et al., 1992). When expressed as percentages, by multiplying η_P by 100, these values correspond to thermodynamic efficiencies. Froude efficiency, a component of η_P, specifically reflects the proportion of external mechanical work, $\dot{W}_{ext}$, that contributes to overcoming drag and maintaining forward velocity. Although breaststroke can exhibit relatively high η_P due to effective force application during the leg kick and arm pull phases, its η_F tends to be lower because of the pronounced intracyclic velocity fluctuations and increased hydrodynamic drag, which reduces the proportion of generated force that contributes to steady forward motion.

Arm stroke efficiency in swimming is commonly represented by Froude efficiency (η_F), which has been identified as a key determinant of swimming performance (Toussaint et al., 1989; Zamparo et al., 2014). Several methods have been proposed to estimate η_F, but it remains unclear whether these approaches yield accurate and reliable results. The power-based method estimates external mechanical power output ($\dot{W}_{ext}$) relative to the metabolic power input, as well as the useful propulsive power, i.e., the power required to overcome drag ($\dot{W}_d$), at a given swimming velocity (Toussaint et al., 1988). In contrast, the speed-based method estimates η_F as the ratio between body´s average forward velocity and the tangential velocity of the hand, assuming that propulsive and drag forces are equal at constant velocity (Martin et al., 1981). This theoretical approach was later adapted into a simplified paddle-wheel model to estimate η_F during only the underwater phase, over half a swimming cycle (Zamparo et al., 2005).

Froude efficiency tends to decrease with increasing velocity, mirroring the decline in stroke length (Peterson-Silveira et al., 2017). A significant correlation exists between the two variables, with higher η_F values associated with longer SL (Zamparo et al., 2005, 2014; Toussaint & Hollander, 1994). Therefore, if a swimmer can reduce stroke frequency and increase stroke length at a given velocity, η_F improves, and energy cost is reduced. Lower η_F values have been reported for backstroke compared to front crawl (Gonjo et al., 2018). These differences in efficiency correspond to variations in C between the two techniques. However, to date, no η_F data have been reported in the literature for butterfly or breaststroke.

In all four competitive swimming techniques, both hydrodynamic drag and propulsive forces fluctuate throughout the swimming cycle. The motor actions of the upper and lower limbs and trunk are more or less discontinuous (especially in breaststroke and butterfly). Thus, in each swimming cycle, the velocity changes as a result of the positive and negative accelerations induced by the continuous variations of the resultant mechanical impulse. This non-uniform movement pattern can be quantified by assessing the intra-cyclic variation of the center of mass's horizontal velocity (dv) (Miller, 1975; Barbosa et al., 2010; Van Tilborgh et al., 1988; Vilas-Boas, 1996). Larger intra-cyclic variations of the impulse induce an additional mechanical work and, consequently, higher C, in order to overcome inertia and drag force (Barbosa et al., 2010). Among the four techniques, front crawl and backstroke typically exhibit smaller velocity fluctuations within the stroke cycle, likely due to the continuous nature of their propulsive phases and the more stable body alignment (Holmér, 1974; Maglischo et al., 1987). In contrast, breaststroke and butterfly show greater dv values (Craig & Pendergast, 1979).

Active drag (D_a) is defined as the water resistance associated with the swimming motion (Clarys, 1979). It is the force opposite to displacement that swimmers have to overcome while attempting to maintain their movement through the water. Several techniques were developed to assess D_a, such as the velocity perturbation method (VPM) (Kolmogorov & Duplishcheva, 1992), which can be applied in all four swimming techniques. VPM relies on the assumption that the swimmer is able of delivering a constant useful mechanical power output. The swimmer performs two maximal effort trials, one with a known additional resistance and one without. As the power output is equal in both conditions, the observed difference in velocity should be due to the effect of the added resistance. Breaststroke exhibits higher D_a values compared to other swimming techniques and, notably, its D_a is approximately twice as high as its passive drag, a difference that is less pronounced in the other techniques (Gatta et al., 2015; Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997, 2021; Xin-Feng et al., 2007).

Breaststroke is known as a very challenging swimming technique because of the discontinuous propulsive action of the arms and legs and the complexity of its time synchronization (Leblanc et al. 2007; Sammoud et al., 2018). Within a breaststroke cycle swimmers decelerate twice. During the underwater recovery of the upper and lower limbs and between the lower limb and the upper limb propulsive phase (Leblanc et al., 2007; Gourgoulis et al., 2018). These repeated interruptions in propulsion dominance, combined with the inherently high D_a characteristic of this technique, contribute to increased dv and elevate the C.

The breathing action disrupts streamline and propulsion in swimming, as the head must deviate from its optimal position to allow air intake. A reduced breathing technique is often used, mostly in the butterfly and front crawl technique, as a way to keep a high velocity while staying in a more streamline position, and therefore reducing drag. Since hydrodynamic drag is directly proportional to the swimmer's projected frontal area, breath-holding or lower breathing frequencies tend to yield better kinematic outcomes. The impact of breathing has been examined in front crawl and butterfly techniques. In front crawl, studies have reported a reduction in swimming velocity during 25 m trials when breathing at higher frequencies compared to non-breathing or breathing every four to six cycles (Couto et al., 2015; Pedersen & Kjendlie, 2006). In butterfly, it was observed a 10° increase in trunk inclination during inhalation (Hahn and Krug, 1992), and reported greater trunk inclination with frontal breathing compared to breath-holding (Alves et al., 1999). Additionally, a reduction in the relative duration of the arm propulsion phase when breathing in butterfly was found (Seifert et al., 2010).

In the breaststroke technique, swimmers usually take an inspiration in each swimming cycle. However, to inhale, the head and part of the trunk must rise substantially from the water level, increasing the frontal surface area and consequently drag. According to the World Aquatics rules (2017–2021), some part of the swimmer's head must break the water surface during each complete cycle, but a full elevation of the head and torso is not required. This indicates that it is not mandatory to breathe on every cycle, which can suggest that reducing breathing frequency may help minimize frontal surface area, decrease drag and potentially lower the C. A gap in the literature was identified concerning the use of a reduced breathing pattern in breaststroke as a potential strategy to maintain high velocity while adopting a more streamlined position, thereby reducing drag, lowering energy cost, and improving efficiency.

In this doctoral thesis, the main objective is to compare and characterize two breathing patterns - breathing every cycle and breathing every two cycles - in the breaststroke technique. Specifically, this thesis aims to: (1) characterize and compare these two breathing patterns based on kinematic parameters referenced to a fixed point (hand, foot, head, and center of mass) in different planes of the breaststroke swimming technique; and (2) compare the effects of these different breathing patterns on energy cost, kinematics, efficiency and active drag in breaststroke swimming. It is hypothesized that a reduced breathing technical pattern will reduce energy cost, decrease active drag, and improve performance.

The current thesis comprises ten chapters. **Chapter 1** introduces the biomechanical and energetic foundations of swimming performance, emphasizing the unique challenges of breaststroke and the potential influence of breathing patterns on hydrodynamic drag and energy cost. Additionally, it is presented and described all the chapters of this dissertation, particularly **Chapters 2** through **6,** where it is featured a systematic review and four experimental studies are presented. In **Chapter 7**, the General Discussion relates to each other and compares the results obtained in our experimental studies with relevant literature, and in **Chapters 8, 9** and **10** are contained the main conclusions of this dissertation, suggestions for future research and the respective bibliographic references.

Chapter 2 presents a systematic review aimed at synthesizing the current body of knowledge on the kinematic, energetic, and hydrodynamic determinants of C variability in the breaststroke technique. Swimming performance is fundamentally driven by energetic factors, which are, in turn, shaped by the swimmer's biomechanical behavior and motor strategies (Barbosa et al., 2010). C is not determined by isolated physiological, biomechanical, or motor control factors, but rather by the complex interplay among them. For instance, swimming v and its dv are global performance indicators, as they emerge from the balance between propulsive forces and hydrodynamic drag, both of which are influenced by coordination patterns and limb synchronization. Biomechanical characteristics like longer stroke length, lower dv, and well-timed inter-limb coordination reduce the C by enhancing propulsion and minimizing resistive forces. Higher segmental velocities during propulsive phases and reduced drag during recovery phases are essential to maximizing forward motion while reducing C. Therefore, understanding how biomechanical, physiological, and neuromotor factors interact in the breaststroke technique, and how this interplay influences C, is essential for advancing knowledge and optimizing performance in this swimming technique.

Several studies have investigated the effects of controlled breathing frequency on bioenergetic responses in swimming, particularly examining variables such as blood lactate concentration ($[La^-]$) and heart rate. However, the existing literature has been limited almost exclusively to the front crawl technique, and the findings remain inconclusive. Some studies reported no changes in $[La^-]$ following various swimming protocols, including 400 m maximal efforts, incremental 7×200 m sets, tethered and free-swimming trials, and 100-yard swims, when using controlled breathing frequencies (Kapus et al., 2003; Key et al., 2014; Murlasits et al., 2023; West et al., 2005). In contrast, lower heart rate and ventilatory responses were observed under controlled breathing conditions (West et al., 2005; Key et al., 2014), while other studies noted no changes in carbon dioxide production or respiratory exchange ratio (Dicker et al., 1980). Interestingly, Holmér and Gullstrand (1980) reported reduced post-swim $[La^-]$ with controlled breathing compared to self-paced breathing during both 100- and 200-yard swims.

In breaststroke, however, literature is much more limited. Zompanakis et al. (2021) found that breathing every cycle resulted in higher $[La^-]$ following a 25 m sprint compared to breathing every three cycles. Notably, the latter condition also yielded faster performance times (19.3 ± 1.6 s vs. 19.5 ± 1.6 s). Building on these insights, **Chapter 3** of this thesis aimed to compare the effects of two different breathing patterns in breaststroke, breathing every cycle versus every two cycles, across a wide range of intensities. This study focused particularly on C and associated bioenergetic variables, providing new insights into how breathing frequency may influence physiological variables in breaststroke swimming.

The C of swimming increases with higher D_a, making drag minimization a key factor in improving swimming efficiency. A “smooth” and efficient swimming technique, particularly one that minimizes the projected frontal area during motion, can thus be expected to reduce D_a and, consequently, lower C. As breaststroke is known to be the swimming technique with the highest D_a values (Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997, 2021), and since reducing breathing frequency in other swimming techniques has been reported to enhance performance, likely by decreasing the frontal surface area, we conducted the study presented in **Chapter 4**. The aim was to compare D_a, the coefficient of hydrodynamic drag force (C_{Da}), and total external mechanical power ($\dot{W}_{ext}$ or P_{tot}) between two breathing patterns in breaststroke: breathing every cycle versus every two cycles.

High dv increases the mechanical work required to maintain a given swimming v, due to the repeated need to overcome both inertia and drag. A smoother motor pattern, reflected in reduced dv, is therefore expected to reduce C. In fact, part of the variation in C across swimming techniques can be attributed to differences in dv. These effects are more pronounced in breaststroke and butterfly, where dv tends to be higher (e.g., Vilas-Boas, 1996; Barbosa et al., 2005), compared to front crawl and backstroke, which are characterized by lower dv values (e.g., Figueiredo et al., 2013; Gonjo et al., 2018). In breaststroke, the existence of different technical variants (Persyn et al., 2005; Vilas-Boas & Santos, 1994), such as flatter or more undulatory patterns, also contributes to variations in C. The timing and magnitude of undulation influence D_a, likely through changes in frontal surface area, and may also affect η_P. Indeed, these technical differences have been linked to variations in swimming economy (Vilas-Boas & Santos, 1994). Additionally, the duration of the glide phase in breaststroke has been shown to influence C at a given velocity (Seifert et al., 2014). In such cases, variations in C were not attributed to changes in frontal area (and thus D_a), but rather to differences in dv and inter-limb coordination.

The dv is a parameter rooted in classical linear kinematics, representing the magnitude of variation in a swimmer's velocity time series relative to its mean value (Barbosa et al., 2005). It offers researchers and practitioners a practical, straightforward means of assessing the forces acting upon the swimmer (Craig & Pendergast, 2006; Seifert et al., 2014). However, some authors have raised concerns regarding the sensitivity of dv (Figueiredo et al., 2012; Psycharakis & Sanders, 2009). To complement such linear measures, it has been suggested that nonlinear dynamic approaches may offer additional insight into motor behavior. Unlike linear systems, where changes in input produce proportionally predictable changes in output, nonlinear systems exhibit sensitive dependence on initial conditions, meaning that small input variations can lead to disproportionately large or complex outputs (Abarbanel et al., 1993). Because of this sensitivity, nonlinear parameters may capture subtle patterns or irregularities in movement that linear metrics like dv may overlook, making them valuable tools for analyzing the complexity and stability of swimming performance.

Fractal dimension (FD) is a nonlinear metric that quantifies the complexity and irregularity of time-series. In the context of swimming, FD offers a complementary perspective on the temporal structure of intra-cyclic velocity fluctuations, capturing patterns that linear measures such as dv might overlook. While dv reflects the magnitude of variation in swimming velocity and can be interpreted as an outcome of the swimmer's motor behavior, FD provides insight into the underlying complexity of that behavior. Given that motor behavior often exhibits nonlinear properties, dv may, in fact, result from more complex dynamic interactions within the neuromuscular system, interactions that FD is better suited to detect (Higuchi, 1988). FD values typically range from 0 to 3, with higher values indicating greater complexity in the movement pattern. Considering the limited literature on breaststroke breathing patterns and the emerging relevance of nonlinear measures in swimming analysis, **Chapter 5** investigates the effects of breathing frequency on breaststroke kinematics and FD, aiming to deepen the understanding of the effects of breathing frequency on breaststroke kinematics and in fractal dimension.

A swimmer's technical ability, namely, their propelling efficiency and ability to overcome drag, along with overall efficiency, has a strong influence on C at a given v (Zamparo, 2006). In breaststroke, efficiency has been evaluated using several indices. These include dv and the stroke index, which relates stroke length to velocity and reflects the swimmer's ability to maintain speed with fewer strokes (Craig & Pendergast, 1979; Costill et al., 1985). Additionally, coordination indices have been used to evaluate the timing and overlap of limb actions, offering insights into inter-limb synchronization and propulsion effectiveness (Leblanc et al., 2005; Seifert & Chollet, 2005). Vilas-Boas (1993) also proposed three additional breaststroke-specific indices: the horizontality index, the anterior-posterior stabilization index, and the total anterior-posterior stabilization index; to assess efficiency from a propulsive segment's stability perspective. However, these have not been further investigated in the literature.

Despite these efforts, studies indirectly assessing hands, feet, and global propulsive efficiency in breaststroke remain scarce. **Chapter 6** addresses this gap by introducing adapted indices of propulsive efficiency specific to the breaststroke technique, namely, hands, feet, and global efficiency measures, and comparing them under two different breathing conditions: breathing every cycle and breathing every two cycles. Additionally, the chapter examines parameters related to anterior-posterior stabilization of the hands and feet in the sagittal plane, as well as feet displacement, to assess their influence across breathing patterns and their relationships with C and D_a.

Chapter 2. Variability of energy cost in breaststroke technique: a systematic review

Miriam Alves[1,2,3]*, Tiago M. Barbosa[4,5], João Paulo Vilas-Boas[1,2,3]

[1] Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D);

[2] Porto Biomechanics Laboratory (LABIOMEP-UP);

[3] Faculty of Sport, University of Porto, 4099-002 Porto, Portugal;

[4] Department of Sport Sciences, Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal;

[5] Research Centre for Active Living and Wellbeing (LiveWell), Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal

Alves, M., Barbosa, T. M., & Vilas-Boas, J. P. (2024). Variability of energy cost in breaststroke technique: a systematic review. *Sports biomechanics*, 1-41. https://doi.org/10.1080/14763141.2024.2427683

Abstract

This study aimed to synthesize the body of knowledge on kinematics, active drag and energetics determinants of energy cost variability in the breaststroke technique. Methodological procedures considering the standards for systematic reviews according to the ‘‘Preferred Reporting Items for Systematic Reviews and Meta-Analyses’’ were employed. Searches were conducted in four prominent databases. A total of 1,464 articles were identified, of which 201 met the eligibility criteria. After evaluation, 73 articles were included for synthesis in this review. The included studies had a mean score (± SD) of 9.14 ± 1.76 points regarding the quality assessment. The present review identified three distinct domains of variables: kinematics (including stroke kinematics and coordination parameters), active drag, and energetics. The findings underscored the pivotal role of stroke kinematics, including stroke rate, stroke length, stroke index, and intra-cyclic variations of velocity, in influencing energy cost during breaststroke swimming. Additionally, the analysis highlighted the significance of propulsive and non-propulsive phases, arm-to-leg timing, and buoyancy in breaststroke technique. Notably, breaststroke exhibited higher values of active drag, frontal area, and energy cost, while maintaining lower velocity compared to other swimming techniques. Overall, this synthesis of literature highlights the holistic nature of energy cost in breaststroke swimming.

KEY-WORDS: SWIMMING; KINEMATICS; COORDINATION; ENERGY EXPENDITURE; ACTIVE DRAG

1. Introduction

Swimming is an aquatic locomotion technique based on periodic limb actions to overcome drag force and propel the body forward in the water (Barbosa et al., 2013). Because of the nonconstant nature of the propulsive and resistive forces acting on a swimmer's body, its locomotion is characterized by accelerations and decelerations, even within a single stroke cycle. This fluctuation of the swimmer's velocity within a stroke cycle is paramount and deemed as a swimming efficiency proxy (Gourgoulis et al., 2018). Active drag is the water resistance acting upon the swimmer during the dynamic swimming motion. A swimmer's ability to swim faster is depended upon the ability to either generate an increase in mean propulsive force such as to overcome the mean drag force presently acting on the swimmer's motion or to reduce the mean drag force on the body through better streamlining technique, or both (Mason et al., 2011).

Breaststroke is a swimming technique characterized by alternating propulsive actions of the upper and lower limbs, that must have contralateral simultaneous action, and the head must breakout the water surface at least once in each stroke cycle (Leblanc et al., 2007). While the upper limbs are propelling, the lower limbs remain extended, then the upper and lower limbs recoveries occur simultaneously, and, finally, the lower limbs perform their propulsive phase (Leblanc et al., 2010). Several breaststroke styles or variants have been described, such as, for instance, vertical, flat, undulated and undulated with overwater recovery of the arms (Vilas-Boas, 1996; Vilas-Boas & Santos, 1994). Research demonstrated that employing an undulated breaststroke technique with overwater arm recovery resulted in diminished efficiency and increased speed fluctuations compared to both flat and undulated breaststroke styles (Vilas-Boas, 1996). Colman et al. (1998) broke down the breaststroke into six variants based on the amplitude of undulation and showed that the most undulating style had less speed fluctuation. In the flat breaststroke, the paths of hands and legs are less vertical and more backward than in undulated styles, and the upward and downward movements of the body are less pronounced (Leblanc et al., 2005).

Performance is strongly underpinned by energetic variables and these are dependent on the biomechanical behavior and motor strategies adopted by the swimmers (Barbosa et al., 2010b). The swimmer's technical ability (i.e., the subject propelling efficiency plus the ability to overcome drag), and the overall efficiency, strongly affect the energy cost (C) at a given velocity (Zamparo, 2006). Swimming velocity (v) is also related to the intra-cyclic variation of the horizontal velocity of the center of mass (dv). Larger intra-cyclic variations of the impulse induce an additional mechanical work and, consequently, higher energy expenditure (Barbosa et al., 2010b). In the literature, the breaststroke technique is consistently identified as having the highest dv and active drag when compared to other competitive swimming techniques (Barbosa et al., 2013; Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997; Kolmogorov et al., 2021). This phenomenon can be attributed to the simultaneity of contralateral actions as well as to the underwater recovery of both the upper and lower limbs, which generates substantial hydrodynamic resistance counteracting the forward motion. For this reason, upper and lower limbs recoveries should not be performed in isolation: expert breaststroke coordination is characterized by synchronized recovery times to diminish this negative time (Chollet et al., 2004; Seifert & Chollet, 2005; Takagi et al., 2004). Furthermore, higher values of dv are correlated with less efficient swimming (Barbosa et al., 2005; Vilas Boas, 1996). In fact, breaststroke has been described as the lowest economic swimming technique (Barbosa et al., 2006; Hólmer, 1992; Kolmogorov et al., 2021).

Recently, a systematic review was carried out with the objective to synthesize the biomechanical factors influencing elite breaststroke swimming performance (Nicol et al., 2022). Nevertheless, a gap in literature persists regarding the consolidation of the state of-the-art on the factors that influence the variations of the energy cost in the breaststroke swimming technique. This study aimed to synthesize the body of knowledge on kinematics, active drag and energetics determinants of energy cost variability in the breaststroke technique. We hypothesized that the variations in kinematic parameters play a significant role in influencing the energy cost variability observed in the breaststroke swimming technique and that active drag contributes to the fluctuations in energy cost during breaststroke swimming.

2. Methods

Methodological procedures considering the standards for systematic reviews according to the ‘‘Preferred Reporting Items for Systematic reviews and Meta-Analyses’’ (PRISMA) statement were employed (Page et al., 2021). The present review was registered on OSF registries on 15 June 2023 (osf.io/g2cp9).

Research sources and eligibility criteria

Scopus, PubMed, Web of Science and EBSCOhost databases were searched by two independent researchers until 31 December 2023 (Supplementary Table 3). Additional records were also identified through other sources (Figure 1). Research articles were included or excluded using the criteria defined by the PI(E)CO strategy (Population, Intervention/Exposure, Comparison and Outcome) (Methley et al., 2014) (Table 1). Only English original research articles were considered. After eliminating duplicates, results were screened according to the title and abstract in the ENDNOTE program (reference management software) to exclude any irrelevant articles. Then, the full-texts of potentially eligible studies were retrieved and independently evaluated for inclusion and synthesis.

Table 1 - Search strategy and inclusion/exclusion criteria based on PICO strategy.

Search terms		PI(E)CO	Inclusion criteria	Exclusion criteria
Swimmer* Competition* Human* Athlete*	Young* Adolescent* Female* Male*	Population	Healthy swimmers	Non-swimmers Paralympic swimmers Master swimmers Triathlon athletes
Breaststroke		Intervention and exposure (i.e., design)	Longitudinal studies Cross-sectional studies	Does not include breaststroke technique
“Energy cost” “Energy expenditure” “Metabolic power” “Active drag” Kinematic “Intra cyclic velocity” “Intracyclic velocity”	“Speed fluctuation” “Stroke length” “Stroke distance” “Stroke rate” “Stroke frequency” “Stroke index”	Comparison	Kinematics Active drag	Does not include these variables
		Outcome	Energy cost	

Note: Asterisks denote truncation to retrieve words with different endings.

Research strategy and results extraction

Two independent researchers performed the selection process of relevant articles. First, all the studies obtained from the search of the databases were inspected, duplicate articles were removed, and titles and abstracts were independently screened. The researchers applied the eligibility criteria defined above and disagreements were discussed until consensus was reached. Then, the same procedure was conducted after full-text screening of the remaining articles for the final inclusion or exclusion decision. Finally, the reference lists of the included articles were checked for relevant articles that might not have been identified in the initial databases search. The extraction process was conducted by one researcher and double-checked by another independent researcher. The items extracted were: 1) study reference; 2) main purpose; 3) demographics (i.e., number of participants per sex, age, and competitive level); 4) breaststroke test performed; 5) variables measured (i.e., outcomes); and 6) main findings. If there were papers with missing data or potential errors in the included data, the researchers discussed and either maintained the article (mentioning the missing data) or removed it from the included ones. When there were discrepancies between data extracted and the double-checking, the divergence was discussed between the two researchers until consensus was reached. The Kappa coefficient reached a value of 0.97, indicating a high level of agreement between the two independent researchers.

Assessing risk of bias

The quality of eligible studies was assessed using the risk of bias scale developed by Hindle et al. (2019b). This instrument was adapted for the assessment of sports research from other evaluation checklists (Hindle et al., 2019a; Natera et al., 2020). The scale features 16 standards: three standards for the study design, four standards for the sample characteristics, four standards for the methodology, and five standards for the results and discussion. One point is awarded for each standard met to a maximum total of 16 points. Risk of bias score is subsequently determined using the total number of points awarded. Articles scored ≥ 11 points are categorized as “low bias risk”, and articles scored 5–10 points are deemed as “satisfactory bias risk”. Scores of < 5 are categorized as “high bias risk”. Only articles with a low or satisfactory bias risk were included in the present review.

3. Results

In the first main search, 1464 articles were identified and 261 duplicates were removed. After the screening of titles and abstracts, 201 articles were accessed for eligibility. Seventy-three articles were included for synthesis, of which nine were identified by other methods (Figure 1). The characteristics of the included studies are shown in Table 2. Regarding the quality assessment (Supplementary Table 4), the included studies had a mean score (± SD) of 9.14 ± 1.76 points (range: 5 to 13 points). Fifteen papers were categorized as low bias risk and 58 as satisfactory bias risk. None of the studies got a score in the item related to the description of "how the study size was arrived at". All studies scored a point in the standards "The results are well described" and "The information provided in the paper is sufficient to allow a reader to make an unbiased assessment of the findings of the study".

Thirty-three studies analyzed both sexes (i.e., males and females) (45.2%), 25 papers recruited only males (34.2%), five just females (6.8%) and ten did not specify the participants' sex (13.7%). As far as the competitive level of the participants is concerned, it varied within all levels. Most articles recruited national (13.7%), elite (15.1%), regional to national (9.6%), international (11.0%) and national to international swimmers (5.5%). Other competitive levels were mentioned but only studied by one or two articles, including recreational to Olympic-level swimmers. The chronological age most often recruited was older than 18 years (45.2%) or aged between 15 and 18 years (21.9%). Ten studies evaluated multiple age-groups (13.7%), five studied participants between 12 and 15 years old (6.8%) and 11 articles did not mention the age of their subjects (15.1%). The age-group below 12 years-old was not reported in the included studies.

For the type of tests implemented, 38 articles selected maximum tests (52.1%) while the others used maximal and submaximal (19.2%), incremental (12.3%), competitive pace (6.8%), submaximal (6.8%), free-swim (2.7%) and incremental and all-out trials (2.7%). When considering the different domains of the variables in the studies that were included, 44 reported kinematic variables (60.3%), of which 26 assessed stroke kinematics variables such as stroke length (SL), stroke index (SI), stroke frequency (SF) and dv and 18 focused on coordination parameters. In addition, five articles focused on hydrodynamic drag (6.8%) and 12 on energetics (16.4%), such as oxygen uptake (VO_2) and blood lactate concentration ([La-]). Finally, nine papers studied both energetics and kinematics (12.3%), one paper reported both drag and energetics (1.4%), and two papers studied both coordination and energetics (2.7%). The most studied variables among the articles were SR (55.9%) and SL (51.5%). Stroke phases (22.1%) were also common among papers, as well as dv (20.6%), [La-] (20.6%) and VO_2 (17.6%). Fewer studies evaluated C (10.3%), SI (8.8%), active drag (10.3%), time gaps (8.8%) and energy expenditure (7.4%).

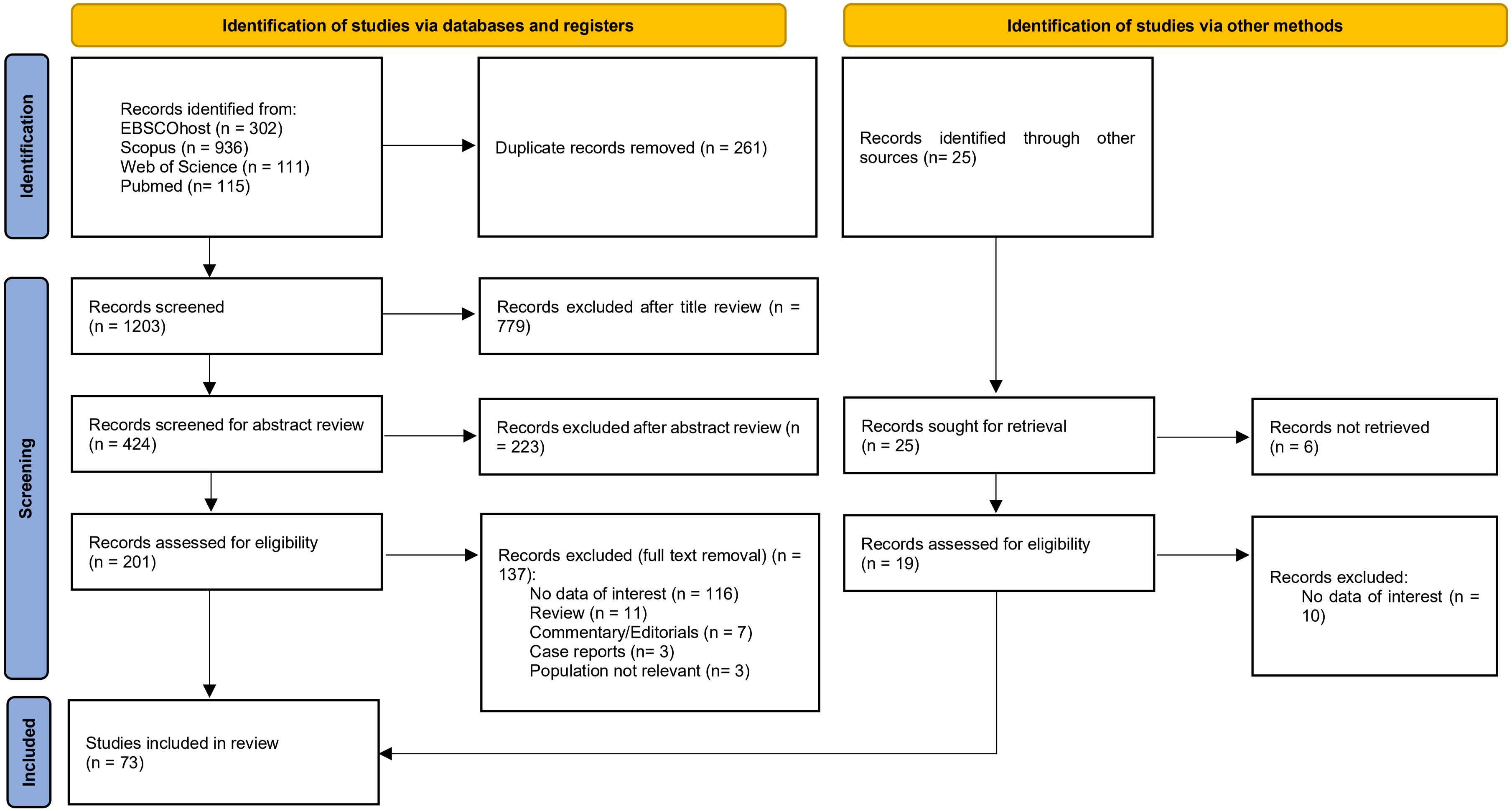


Figure 1 - Summary of PRISMA flow for search strategy.

Table 2 - Summary of the main aim, participants´ demographics, selected variables and main results of the included studies.

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Arellano et al. (2022)	To verify the variables that determined the differences between swimmers who reach the finals and those who did not.	56 international level males (23.78 ± 3.25 years); 60 international level females (24.66 ± 4.12 years)	50m (maximal)	SR and SL (15-25m, 35-45m and final)	Women were able to increase SR especially during the final and it was related to improved performance; men maintained similar SR values throughout the race, however, between rounds SR increased resulting in a reduction of the glide phase and thus SL. No changes for the 15m time in the different rounds. 15m time was shown to predict 25m time, but not 50m time.
Barbosa et al. (2006)	To measure and compare the total Etot of the four competitive swimming techniques.	18 of international level males and 8 females (5 Br)	7x 200m (incremental)	Etot	Fc was the most economical technique, followed by the Bk, the Bt and the Br for all selected v
Barbosa et al. (2008)	To analyze the relationships between C, v, SF and SL	3 males and 2 females elite level (17.40 ± 1.10 years)	n x 200m (incremental)	C, v, SR, SL	Increases of SR were associated to increases of C, even when controlling v. Increases in the SL promoted significant decreases of C, even when controlling v. Increase of v promoted an increase of C.
Barbosa et al. (2010a)	To assess the kinematical changes when swimming maximal bouts in Br with the AquaTrainer® snorkel.	7 national level swimmers (19.10 ± 4.30 years)	2x 100m (maximal)	SR, SL, SI, dv	100m time was higher during snorkel swimming when compared with free swimming. No significant differences were found in any stroke parameter, although some smooth kinematical changes were verified for the stroke technique due to added drag.
Barbosa et al. (2013)	To assess the relationship between the dv and the v of the 4 competitive	23 males and 22 females regional to national level (12.78 ± 1.15 years)	4x 25m (maximal, one in each swimming technique)	dv	The dv was higher in the Br. In Br dv was characterized by a 2-peak profile.

	swimming techniques				
Barbosa et al. (2016)	To compare the non-linear properties of the four competitive swim techniques.	34 national to international level males (17.06 ± 4.11 years) 34 national to international level females (14.97 ± 2.96 years)	4x 25m (maximal, one in each swimming technique)	dv, ApEn, Fd	The ApEn showed the lowest value in Fc, followed by the Br, Bt, and Bk. Fractal dimension had the highest value for the Br. The highest dv was for the Br technique.
Barbosa et al. (2017)	To examine the variation of linear and nonlinear proprieties of the behavior in participants with different levels of swimming expertise among the four swim techniques	21 males and 4 females highly qualified expert level (15.73 ± 1.52 years) 11 males and 14 females expert level (15.74 ± 3.55 years) 18 males and 7 females nonexpert level (22.86 ± 3.40 years)	4x 25m (maximal, one in each swimming technique)	dv, ApEn, Fd	Br featured the highest dv and Fd. A lower ApEn was found for Br. The dv was higher in non-expert swimmers than their expert or highly qualified expert counterparts.
Bartolomeu et al. (2018)	To assess the effect of the limbs' actions on the nonlinear properties of the four competitive swimming techniques	24 males and 25 females regional to national level (14.20 ± 1.71 years)	12x 25m (maximal, 3 in each swimming technique in the conditions: full cycle, arms-only and leg kicking)	dv, SampEn, Fd	Br was the slowest technique and presented the lowest value of SampEn and highest values of Fd. Leg kicking was the slowest condition in all techniques with the exception of Br. The highest dv was in the Br.
Capelli et al. (1998)	To determine the C of swimming at different v in the four swimming techniques	20 elite level males (18.90 ± 0.94 years)	2.50 min in an annular pool (submaximal) 45.70 m, 91.40m and 182.90m (maximal)	C	C increased monotonically with v. Br was the least economic technique.

Carvalho et al. (2020)	To confirm the AnT as the boundary above which [La-], SR and SL exhibit significant changes	47 international level males (20.30 ± 3.10 years) 25 international level females (18.40 ± 2.50 years)	5x 200m (incremental)	[La-], SR, SL	v at AnT in Br was considerably lower than all other swimming techniques. Inflection points of SR and SL vs. v corresponded to v at AnT.
Chollet et al. (1996)	To compare stroking parameters such as SL and SR used by female and male top level swimmers during competition on 100 and 200m events in each technique	377 national to international level males 369 national to international level females	200, 100m (maximal)	SR, SL	100/200 SR difference was the greatest in Br. 200m SL was higher than that of 100m. No differences in SF were found between males and females, so SL was the main contributor to the higher v in male swimmers.
Chollet et al. (2004)	To propose a new method to evaluate arm-leg coordination in flat Br.	9 national to international level males (19.90 ± 2.30 years) 7 national to international level females (15.70 ± 1.20 years)	200, 100, 50m (maximal)	SR, SL, SP, TG, ESP	A faster pace corresponded to increased SR, decreased SL, increased propulsive phases, shorter glide phases and a shorter effective body glide. The top-level swimmers showed short time gaps which reflected the continuity in arm and leg actions.
Colman et al. (1998)	To establish differences in dv of the body's CM in Br swimmers with flat and undulating styles	25 international level males (19.90 ± 2.60 years) 20 international level females (17.90 ± 3.07 years)	25m (100m competitive pace)	dv	Undulating style presented less dv of the body's CM.
Conceição et al. (2013a)	To observe and characterize the Br technique concerning the correlation between kinematic and neuromuscular parameters in a 200m Br event	12 national level males (22.30 ± 2.90 years)	200m (maximal)	SL, SR, [La-]	SL decreased from the first 50m distance to the fourth 50m distance. SF decrease from the first 50m distance to the third 50m distance, slightly increasing in the last distance. The lactate concentrations increased from rest to the [La-] peak after the 200m. SL demonstrated strong

					correlation with SF, when SL increases, SF decreases.
Conceição et al. (2013b)	To examine the characteristics of waves generated when swimming with and without the use of Aquatrainer® snorkels	8 national level males (21.25 ± 6.73 years)	2x 25m (maximal)	SL, SR, SI, St	The use of the Aquatrainer® snorkel in the Br showed a lower SL, SI and v and a higher SF compared to the normal condition.
Craig & Pendergast (1979)	To study the basic relationships between SR, SL and v in competitive swimmers	110 competitive level 223 olympic level	n x 22m (incremental)	SL, SF, dv	Increases in v were associated with increases in SF but SL decreased much more than in the other techniques. dv values were the highest in Bt and Br.
Cuenca-Fernández et al. (2023)	To investigate performance variation in all race sections, i.e., start, clean swimming, and turns, of elite short-course races for all swimming strokes and to determine the effect of performance variation on race results.	64 males finalists (23.7 ± 2.8 years) 34 males semi-finalists (23.8 ± 3.4 years) 64 males non-qualified (23.0 ± 3.4 years)	100 and 200m (maximal)	SR and SL	In the 100 m races, SR changed/increased the most in third lap, with similar trends for both the first and second lap.
di Prampero et al. (2008)	To compare the critical v, calculated by taking into account the effect of a non-constant C, with the slope of the distance versus time relationship.	20 elite level males (18.90 ± 0.90 years)	45.7, 91.4 and 182.9m (maximal)	VO_2max, C, Etot	Br presented the highest value of C and lowest critical v value compared to the other swimming techniques.
Gonjo et al. (2023)	To investigate differences throughout 100m breaststroke between elite and sub-elite	14 males breaststroke specialists (20.0 ± 2.4 years) 7 males sub-	100m (maximal)	v	Elite swimmers had a larger mean clean-swimming v than sub-elite swimmers in all laps due to the shorter clean-swimming duration. On the other hand, no differences between

	swimmers using time-series velocity data.	specialists (17.7 ± 0.9 years)			the levels were observed in the pull-out segment variables.
Gatta et al. (2015)	To use the planimetric method to determine Ap throughout the stroke cycle in the four swimming techniques and during 'streamlined leg kicking'.	6 highly trained males (21.30 ± 0.50 years) 4 highly trained females (20.80 ± 0.50 years)	Swims in the 4 techniques and leg kicking	Ap, Da, nd	Da presented the highest values for the Br technique. Br and Bt showed the highest values of Ap.
Gourgoulis & Nikodelis (2022)	To compare the arm-stroke kinematics during maximal and sub-maximal Br swimming using both discrete and continuous data analysis.	9 males (21.57 ± 4.20 years)	2x 25m (maximal and submaximal)	SP, SL, SR, hand, arm-stroke and CM length, width and depth, hand v in x,y and z axis and SP	Submaximal intensity presented lower v, greater SL and less SR than maximal trials. The absolute and relative duration of the glide phase was longer, while the relative duration of all the other phases was shorter. Additionally, hand v during the arm recovery was slower (in the 3 planes). The main discriminating factor between the two conditions concerns to the adjustment of the glide and the recovery phase and consequently the continuation of the propulsive movements.
Gourgoulis et al. (2018)	To compare the CM and hip dv in Br swimming using 3-dimensional kinematic analysis	9 moderate level males (21.57 ± 4.20 years)	25m (maximal)	CM and hip (in the resultant, x, y and z axis): dv (absolute, relative), SP v, v (min, max, mean), SRT, ALT, SPT; TI	The arm pull and the leg kick result in acceleration of the swimmer's v, whereas the glide and the arm and leg recovery result in deceleration of the swimmer's v. It was observed a steeper increase during the leg propulsive phase, in comparison with the arm propulsive phase, indicating that the acceleration of the swimmer's body produced by the legs was greater than that because of the arms' action. However, this greater acceleration did not produce a higher v than that obtained during the arm propulsive phase, probably because of the much smaller starting v or the limited

					ability of the swimmers to perform an effective leg kick. Despite this similar general pattern, discrepancies between the HIP and CM v curves were observed.
Hellard et al. (2008)	To assess SR variability in elite female swimmers	64 olympic level females (Br: 22.00 ± 3.00 years) 64 national level females (Br: 19.00 ± 3.00 years)	200m (maximal)	SR, SL, v (for full swim, for each 100m)	SL and SR were different for the four techniques. Fc presented the highest SL, followed by Bk, Br and Bt. SR variability was greatest for the Br.
Hermosilla et al. (2020)	To present and validate the SwimOne device for determining instantaneous propulsive force and power	4 regional to national males (22.67 ± 1.15 years)	8x 15 m (with a progression in the opposition force, in each technique)	Fa, MSP	Br presented the lowest Fa value compared to the other swimming techniques. Fc showed the higher values of MSP, following by Br, Bt and Bk.
Holfelder et al. (2013)	to improve the interpretability of lactate diagnostics in swimming by identifying lactate-affecting variables and to present the Multilevel Analysis as a statistical method which is able to analyze the typical data structure in high performance sports in a formally correct way.	228 high performance males (19.10 ± 3.17 years) 170 high performance females (16.94 ± 2.78 years)	5 steps of 100m or 200m or 4 steps of 400m (incremental)	[La-], AT	Overall, the swimming technique seems not to play a key role in terms of affecting lactate parameters. The [La-] of the Br events were the lowest on average in direct comparison with the same distance for the other swimming techniques.
Holmér (1974a)	To study the VO_2 during swimming with arm strokes and leg kicks in the different	19 elite level males (4 Br: 21.30 ± 5.50 years)	2 or 3 steps and 1 step (submaximal and maximal rate of work, in a	VO_2, HR, PV, VC, Dp	In the Br VO_2 was approximately the same in all modes of swimming (whole stroke, arms only, leg kicking) in relation to v. During maximal leg kicking alone in the Br the speed was

	swimming techniques.		swimming flume)		only 10% lower than for maximal swimming with the whole stroke.
Holmér (1974b)	To determine the np of arm stroke, leg kick and whole stroke in the Br and Fc, respectively.	3 top level (25, 17 and 16 years)	5, 4, 4, 4 min with and without extra loads (submaximal, in a swimming flume)	VO_2, Da, Dp, np	Propulsive efficiency in the Fc was found to be greater than in the Br. Leg kicking in the Br displayed a consistently low level of efficiency, and arm stroke in displayed about the same efficiency as the whole stroke.
Kolmogorov & Duplishcheva (1992)	To present a new alternative approach to uncover the relation between Po, Da, the CDa and the maximal swimming v applied to the four competitive techniques.	73 national level	2x 50m (maximal)	Da, CDa, Dp, CDp, Po	Br presented one of the highest values of Da, for the same v, compared to the other techniques.
Kolmogorov et al. (1997)	To describe the hydrodynamic characteristics of the four techniques by gender and performance level.	487 males and 310 females all performance levels (10 to 28 years)	2x 50m (maximal)	Da, CDa, Dp, CDp, Po	According to the hydrodynamic indicators, Da, CDa, Po, in men and women, the swimming techniques were ranked as low to high resistance, Fc, followed by Bk, Bt and Br.
Kolmogorov et al. (2021)	To determine the main biophysical (energetic and biomechanical) reasons for the observed differences in maximal swimming v between the different competitive swimming techniques.	4 males and 4 females elite level (21 to 26 years)	8 × 1 min (incremental, in a swimming flume) 8 × 100m (incremental) 2x 30m (maximal)	Etot, Da, ep	Br presented the highest values of frontal component of Da and Etot.

Komar et al. (2014)	To compare interlimb coordination and indicators of swim efficiency and swim effectiveness between expert and recreational Br swimmers.	5 males and 3 females expert level (20.8 ± 2.1 years) 6 males and 4 females recreational level (20.4 ± 1.5 years)	3x 2x 25m (70%, 90% of maximal pace and maximal)	CRP, CM v (min, max, acceleration, deceleration at different SP), dv, distance covered by the CM (at different SP)	Experts exhibited a more effective arm-leg coordination pattern than recreational swimmers. Experts showed a better management of their arm-leg coordination during the glide phase, namely by maintaining a streamlined position with arms and legs during the glide. Experts and recreational swimmers spent the same time with arms and legs outstretched, therefore the same relative duration of the glide. No differences between the two groups were found in dv.
Lauer et al. (2015)	To provide a predictive equation to estimate de Win of Br swimming and to check its accuracy against Win values measured from kinematic sequences captured at various stroke frequencies and to explore the frequency-internal work relationship in swimming and contrast aquatic vs terrestrial locomotion.	4 elite level males (25.00 ± 3.10 years) 4 elite level females (19.37 ± 6.10 years)	3x 25m (at different self-chosen paces)	Wint, SR	Swimmers were able to moderate the increase in Wint at the highest SR.

Leblanc et al. (2005)	To analyze the arm-leg coordination patterns of two groups of swimmers of different skill levels.	11 males and 9 females national to international level (19.90 ± 2.30 and 15.70 ± 1.20 years) 11 males and 9 females regional level (15.10 ± 0.90 and 14.80 ± 1.20 years)	3x 25m (200, 100 and 50m pace)	SR, SL, SP, TG, ESP	Among each group, the increase of v is related to an increase of SR and a decrease of SL. The Br is the only technique where SL decreases when switching from v200 to v100. For the same SR, elite female and male swimmers had a greater mean v, accompanied with a greater SL, than non-elite swimmers. For the same swimming pace, elite swimmers of both genders have a shorter glide time and proportionally longer recovery and propulsive phases. Elite swimmers are able to swim at the same v as lower-level swimmers, by using a technique with more glide demonstrating a better propulsive efficiency and the ability to cover a longer distance during the non-propulsive phases of the movement.
Leblanc et al. (2007)	To compare the distances covered during each phase of the stroke, dv and the intra-cyclic accelerations in two groups of male swimmers with different skill levels, at three swimming race paces.	9 national level males (19.90 ± 2.30 years) 9 regional level males (15.10 ± 0.90 years)	3x 25m (v200m, v100m, v50m paces)	dv, SR, SL, ADTR, SP	In the two group of swimmers, the switch from the 200m to the 100m and the 50m was associated with a decrease in SL and an increase in SR and swimming v. When race pace increased, the distance covered during the leg arm lag phase decreased, while the distance covered during the recovery phase and the propulsive phases of the arm and leg remained stable for both groups. For the leg-arm lag phase distance, the relative distance pattern tended to remain stable in elite swimmers. In nonelite swimmers, the decreased distance in the leg-arm lag phase was compensated by an increase in the relative distance covered in the arm and the leg propulsive phases. Elite male swimmers were able to simultaneously combine a high

					magnitude of hip dv and a better ADTR, resulting in greater SL.
Leblanc et al. (2009)	To make an accurate assessment of the temporal aspects of the arm–leg coordination of recreational swimmers and to analyze the evolution of the arm–leg coordination under different conditions.	12 competitive level males (16.20 ±1.50 years) 12 regional level males (16.90 ±1.60 years)	2x 25m (v400m and maximal pace)	SR, SL, SP, TG, ESP	Recreational swimmers perform their arm recovery while doing their leg kick, showing a simultaneous extension of their two pairs of limbs and the arm propulsive phase started before the end of the leg in-sweep. Arm's recovery phase of recreational swimmers was longer than competitive swimmers. In recreational swimmers, the end of the extension of the lower and upper limbs was simultaneous. Recreational swimmers, having no glide time, can hardly modulate their coordination according to the swimming v.
Leblanc et al. (2010)	To measure swimmers' floatation parameters and to relate these data to their stroking characteristics.	23 club-level males (16.00 ± 2.20 years) 23 club-level females (15.30 ± 1.70 years)	2x 25m (v200m and v50m pace)	SR, SL, SI, SP (% and v), hydrostatic lift (N), sinking force (N), maximum glide length (m)	Female swimmers had greater hydrostatic lift and a smaller sinking force magnitude compared with male swimmers. In the female group, the hydrostatic lift and the maximal glide length were positively correlated with glide phase, the mean glide v and SI. In male swimmers, the sinking force was negatively correlated with glide phase and mean glide v. In both group of swimmers, the impact of floatation appeared of less importance at sprint pace.
Lomax et al. (2022)	To characterize the VO_2 kinetic response during moderate-intensity in Fc and Br and to compare the ventilatory and metabolic responses to moderate-intensity and maximal v in Fc	4 males and 4 females trained (20.00 ± 1.00 years)	2x progressive until Tlim (in a swimming flume) 3 or 4x 6min (at 80% of the v at VT in a swimming flume)	VO_2max	vVT and maximal v were slower during Br. All other ventilatory and metabolic parameters, including VO_2max, are similar between Fc and Br during maximal swimming. During moderate-intensity, VO_2 kinetics and both the ventilatory and metabolic responses were similar between the two techniques.

	and Br flume swimming.				
Marinho et al. (2011)	To determine and analyze AnCV in young swimmers comparing it with short distances performances in the 4 swimming techniques.	12 males and 8 females (12.10 ± 0.72 years)	10, 15, 20 and 25m (maximal)	AnCV	Relationships were found between the values of AnCV and the 50, 100 and 200m swimming event v in Br.
Mason (1989)	To obtain information about the dv and acceleration profiles of elite Br swimmers and to identify if this information could be used to evaluate the technique efficiency of swimmers involved in the study so that any disclosed inefficiencies could be eliminated.	9 national to international level	2x 25m (maximal)	dv, CM (v, displacement and acceleration)	Three distinctive propulsive stages were observed in Br swimming. The first was biphasic and was associated with the hand pull and the insweep of arms and hands. In some swimmers this second aspect was almost nonexistent. The second propulsive stage was not associated with any particular propulsive action of the swimmers. The third propulsive stage was the largest and this was attributed to the leg kick.
Morouço et al., 2011	To characterize the force profiles of elite swimmers, through tethered swimming, in the four competitive techniques, identify the relationship between tether forces and swimming v, and to see if relative values of force production are better estimators of swimming performance than absolute values.	20 international level males (19.00 ± 2.88 years) 12 international level females (15.30 ± 1.68 years)	2x 30sec (maximal, tethered swimming)	Fmax, Fmean, Fatind	The simultaneous techniques (Br and Bt) presented both higher and lower values of force production, inducing maximum forces higher than the alternated techniques (Fc and Bk). Br swimmers recorded the highest tethered swimming force values. Br v50m presented the highest correlation value with Fmax.

Oliveira et al. (2016)	To analyze the VO_2 slow component of trained Br swimmers during submaximal incremental exercise, using a multiexponential function.	12 high level males (16.90 ± 2.80 years)	4x 300m (incremental)	VO_2, [La-]	Slow component appeared with exercise intensity above the 3.5 mM-1 lactate threshold.
Oliveira et al. (2023)	To understand whether there are significant differences in stroke kinematics between tiers in female swimmers competing in the four 50 m events of the 2021 European Championships and to understand the speed-time relationship in the four race events per tier.	75 female breaststroke swimmers	50m (maximal)	SL, SR and SI	SR had a significant tier effect in all race sections in the 50m race.
Olstad et al. (2017)	To investigate the relationship between muscle activation in eight different muscles and kinematic SP using 3D mo-cap with automatic motion tracking during three different effort levels in elite Br swimmers	4 elite level males (27.70 ± 7.10 years) 5 elite level females (20.30 ± 5.40 years)	3x 25m (200, 100 and 50m pace)	SR, SL, knee: angle, v, absolute, relative duration, distance during different SP	Increased v with increasing effort came from a significant decrease in distance during the knee extended phase combined with a decrease in the duration spent for the knee extended and knee flexion phases. In addition, the knee angle at the beginning of the knee extension decreased with increased effort providing a better mechanical advantage.
Olstad et al. (2020)	To identify segmental factors related to the finishing time in the modern 100m short course Br.	15 high level males (19.00 ± 2.50 years)	100m (maximal)	SL, SR, start, turn, swim, finish segments with	Nearly perfect or very large correlations with the 100m finish time observed in the 15m start time and the 10m turn-out time, even though the 15m start does

				underlying components	not compile most of the finishing time.
Oxford e al. (2017)	To compare arm–leg coordination between each lap of a 100m swim and relate this to changes in swim v, SL, SR and SI and to compare arm–leg coordination, swim v, SL, SR and SI between sexes;	18 competitive level males (18.90 ± 2.20 years) 8 competitive level females (19.10 ± 2.30 years)	100m (maximal)	SL, SR, SI, SP, TG	A decrease in SR from the 1st the 3rd lap of the swim with an increase seen on the final lap was observed. A decrease in SI was also reported through the swim. Though there was a significant decrease in swim v, there were no significant changes in the time spent in each of the SP and in SL over the duration of the swim. Males presented higher SL and v, but there was no differences between sexes in the time spent in any of the phases of the stroke.
Pai et al. (1984)	To determine SL and SF of elite swimmers in the four competitive techniques, to compare the results obtained for male and female swimmers, using the same technique in races over different distances, and at different stages of the same race and to determine the relationships between SL and SF.	16 males and 16 females international level (Br)	100 and 200m (maximal)	SL, SR	A unique pattern of SL and SF combinations for each of the four techniques was found. For Br, males presented higher values of SF in the 100m, but SL values were the same for both male and female swimmers.
Psycharakis et al. (2008)	To investigate and evaluate the relationships between stroke kinematics and [La-] for elite swimmers competing at the international level	11 males (23.00 ± 2.50 years) 10 females (21.30 ± 3.50)	7x 200m (incremental)	SR, SL, [La-]	Swimmers increased v by increasing SR and decreasing SL, while [La-] increased. Similar v were produced with different combinations of SR and SL, while the best combination for reaching a given v varied both between and within swimmers. Changes in SR and SL occurred

	during incremental exercise in their specialist events and distances and, to examine the extent to which changes in these parameters are associated with swimming performance.				rapidly in relation to [La-] during the early stages of the test, when [La-] levels were low.
Reis et al. (2010)	To correlate aerobic and anaerobic physiological measurements either with the subjects' performance in 100m and 200m simulated Br events respectively using the Aquatrainer valve or with the subjects' season best performance in competitions.	22 competitive level males (16.90 ± 2.60 years)	Incremental test 100 or 200m (maximal)	C, [La-], peak VO_2, vpeak VO_2, v2, v4, v2 VO_2, v4 VO_2, VO_2mean, AOD	For the 200m performance was more accurately predicted by the combination of aerobic fraction on energy release, peak blood lactate post-exercise and v2 VO_2, whereas for the 100m it was best predicted by the combination of v4 VO_2 and peak VO_2.
Sánchez & Arellano (2002)	To evaluate the correlation between final time and SI, to compare the SI among swimmers of different levels, to examine the differences across several race distances and swimming techniques and to compare the differences between sexes.	181 males and 313 females world level 217 males and 203 females national level	50, 100 and 200m (maximal)	SR, SI, SL	The Br SI had the smallest value. The SI values of the man's 50m breaststroke events were smaller than the values 200m.

Seifert & Chollet (2005)	To examine differences between the sexes in flat Br arm and leg coordination over three race paces (200, 100 and 50m) and to link arm and leg coordination and propulsion by the calculation of a new IBFP, which measures the total duration of propulsion.	9 elite level males (20.00 ± 2.50 years) 8 elite level females (15.70 ± 1.50 years)	3x 25m (incremental, 200, 100 and 50m pace)	SR, SL, SP, TG, IBFP	The increase in v from the 200m to the 100m event was related to the increase in SR and the decrease in SL. From the 200-m to the 50-m pace, men and women increased their body propulsion due to the increase in upper limb propulsion. They decreased the body glide, which was due to a decrease in arm and leg glide. IFBP was lower for the women than for the men at the fast paces. Men had a longer propulsive phase and shorter glide and recovery phases than the women.
Seifert et al. (2010)	To analyze how swim v and skill level affect upper–lower limbs coupling during a complete Br cycle using the elbow–knee CRP.	12 recreational females (16.50 ± 1.90 years) 12 competitive females (15.70 ± 1.50 years)	2x 25m (80% of maximal and maximal pace)	SR, SL, CRP	Recreational swimmers displayed a superposition coordination, an overlap of arm recovery with leg propulsion or/and an overlap of arm propulsion with leg recovery. Competitive swimmers switched from anti-phase coupling (legs maximally flexed/arms maximally extended) to in-phase (legs maximally extended/arms maximally extended), and during arm propulsion, the swimmers switched from in-phase coupling (legs maximally extended/arms maximally extended) to anti-phase (legs maximally flexed/arms maximally extended). Between arm and leg propulsions, a second part of the cycle was devoted to glide time, which varied from 20% to 40% of the cycle depending on v. Conversely, recreational swimmers spent less time in in-phase mode than the competitive swimmers due to the absence of glide time. V influenced the amount of time spent in in-phase, which decreased from 43% to 33% of a complete stroke between slow v and maximal v.

Seifert et al. (2011)	To analyze the inter-individual variability of swimmers at different skill levels to test the proposed conceptual ‘‘hourglass’’ model of variability.	24 recreational (16.70 ± 1.70 years) 24 competitive (16.10 ± 1.50 years)	50m (maximal) 25m (80% of the maximal pace)	SR, SL, CRP	Recreational swimmers showed a superposition of the propulsion of one pair of limbs with the recovery of the other pair of limbs, whereas competitive swimmers displayed propulsion alternation and glide time. Higher inter-individual variability was observed in recreational swimmers.
Seifert et al. (2014)	To examine how expert swimmers are able to adopt an economic inter-limb pattern of coordination and if they are able to vary this freely chosen coordination pattern to minimize energy.	8 national level Br (18.30 ± 2.10 years)	3x 200m (70% of 200m pace)	SP, TG, C, VO_2, [La-]	C was lower for the freely chosen coordination and no ideal coordination pattern was determined, as the freely chosen pattern emerged from interacting constraints. Swimmers exhibited the highest C when they swam with maximal glide in comparison with minimal glide. Br specialists showed higher coordination flexibility than Fc specialists when coordination was constrained.
Sharp & Costill (1989)	To assess the effect of shaving body hair on physiological responses to free and tethered Br swimming and to examine the effect on v decay during a prone underwater glide after a maximal push from the side of the pool.	13 collegiate level males (19 to 23 years)	365.8m (90% of maximal pace) 8min (tethered, retarding forces 6.27, 7.75 and 9.26kg) 6x maximal underwater leg push-off and glide	SL, VO_2, HR, [La-]	Removing body hair decreased physiological effort (reduced [La-] and VO_2) and increased SL, required to maintain a given v during Br but had no effect on physiological responses during tethered swimming.
Stachowicz & Milde (2023)	To determine the changes in thrust force and effect size of training load in swimmers using four swimming strokes monitored 4 times a year.	5 elite males (22.0 ± 3.1 years)	Thrust force (60 s)	Thrust force changes vs. time	Breaststrokers were able to maintain maximum thrust force for the longest time and their force curves were characterized by the smallest drop before 60 seconds of measurement compared to other swimming strokes.

Staniak et al. (2016)	To develop a method for measurement and analysis of kinematics of the pelvic girdle movement in Br swimming to support training of technical skills.	5 elite males (20.60 ± 2.30 years)	3x or 2x or 1x 50m (submaximal)	acceleration components, angular v of rotation components	Mean duration of the effective propulsion of upper limbs was nearly twice shorter than duration of propulsive activity of upper limbs. The beginning of the range of propulsive motion of the upper limbs was indicated at the moment of obtaining the local minimum of v that occurred after the v maximum connected with lower limb propulsion. The end of the range was found after obtaining the v maximum connected with propulsive activity of the upper limbs.
Stosic et al. (2021)	To examine the effect of the breakout movements on the stroking variables and coordinative patterns of competitive swimmers.	33 national level males (16.50 ± 1.29 years)	4x 25m (maximal, one in each swimming technique)	SF, SL (in different phases), relative duration of each upper, lower limb phase, CRP	In Br, swimmers increased the relative duration of the propulsive phases of the upper and lower limbs during breakout. The average v when transiting from underwater to surface was still lower than the v obtained in free swimming.
Strzala et al. (2013)	To detect the parameters of the time structure of the cycle correlated with the maximal swimming v in order to focus to specific technical aspects in the Br training	23 regional or national level males (15.00 ± 1.17 years)	50m (maximal)	SR, SL, SP, GO, ALL	The reduction of the glide and even overlap of the propulsive movements of the upper and lower limbs influenced the swim v. A faster start of leg propulsion was also associated with the percentage of duration time of leg propulsion in each kick. A correlation was found between v and the execution time of the in-sweep phase of the upper limbs. The overall contribution of time in producing a propulsive force by the lower limbs in the movement cycle significantly influenced v. Trained swimmers could do effective propulsive movements resulting in the achieved higher v by adjusting movement coordination of the proper extremities with shorter or lack of intercyclic glide or overlapping propulsive arm-leg action.

Strzala et al. (2014)	To analyze the coordination, propulsion and non-propulsion phases in the 100m Br race in a group of young swimmers.	27 school or university level males (15.70 ± 1.98 years)	100m (maximal)	SR, SL, SP, TTG, GO	SL and upper limb in-sweep phase were strongly related to 100m v. A negative correlation between part of the arm recovery and v was found.
Strzala et al. (2015)	To examine the influence of selected indicators of somatic properties and physiological capacity on the v in the 200m Br race, to analyze kinematic parameters of Br swimming as well as assessing their impact on the v in the 200m Br race and to test the level of contribution of clear surface Br and turning zones swimming in the 200m Br race.	27 school or university level males (15.70 ± 1.98 years)	200m (maximal) 90s (maximal, in an ergometer upper limbs cranking and cycling)	SR, SL, SP, GO, ALL, TTG, VO_2peak, Wtot of upper limbs cranking, cycling	v of 200m was related to VO_2peak of cycling and Wtot of upper limbs cranking. Turn zones v was strongly correlated to 200m v. v of 200m was positively related to leg total propulsion phase and negatively related to leg total recovery phase and glide. No dependence between percentage of propulsive arm movement and v of 200m was found. As SL decreased, SR increased on the 3rd and 4th 50m sectors of the total 200m.
Strzala et al. (2016)	To examine how coordination and kinematic indices interplay with swimming performance measured by average v in 50m all-out test.	34 university level males (19.10 ± 1.91 years)	50m (maximal)	SR, SL, SP, GO, ALL, TTG, acceleration, angular v components	SR and ample arm propulsion phase duration impulse were highly associated with v. TTG was related to v and SR, indicating the ability to perform effective limb and body movements together with shortening inter-cycle gap-glide or overlap.

Takagi et al. (2004)	To compare differences in SP, arm-leg coordination and dv in Br due to event and performance level for both male and female swimmers at the FINA 2001 World Championship.	46 world level males 35 world level females	50, 100 and 200m (maximal)	SR, SL, SP, SRT, ALT, SPT, dv	SR and SL were inversely related to each other and better swimmers adopted a greater SL than less proficient swimmers. SR values were not significantly different by gender and performance levels. The time from the start of leg propulsion to the beginning of arm propulsion became higher as the distance increased, and it was higher for qualified swimmers than for the eliminated swimmers. For the phase of simultaneous propulsion of arms and legs, there were differences between gender and performance level. As the event distance increased, the value changed from positive to negative, a change indicative of decreasing overlap of propulsion. For the non-propulsive phase of the stroke values tended to increase as the distance increased, with no difference between performance levels.
Thompson (1998)	To test if improved swimming time may be coincident with increased [La-] production during Br competition.	6 national (21.00 ± 3.20 years)	100 and 200m (maximal)	[La-]	The 200m final yielded a greater absolute [La-] than the 100m final
Thompson et al. (2000)	To evaluate the interrelationships between \`swimming' and \`non-swimming' variables and performance, to compare changes in kinematic variables as the swimmers progressed through the race and to make	318 national to elite males 316 national to elite females	100 and 200m (maximal)	SR, SL, finishing, start, turning and end time	Mid-pool v decreased over each consecutive 50m of a race, with the first length being swum faster than the final length irrespective of race distance or sex.SR and SL were not related to finishing time but were negatively related to each other. Mid-pool v, turning time and SL were generally found to deteriorate as the races progressed. Male 200m swimmers were anomalous in that they demonstrated a much

	comparisons between 100m and 200m races.				greater variation in mid-pool v and turning time and poor correlations with finishing time in the latter stages of the race. 100m swimmers exhibited greater mid-pool v and SR coupled with shorter start times, turning times and SL than 200m swimmers.
Thompson et al. (2003)	To investigate the effect of even, positive and negative pacing strategies on selected metabolic, kinematic and temporal variables during Br trials.	9 regional to national males (21.00 ± 3.00 years)	200m (maximal) 3x 175m (even, positive or negative pacing)	SR, HR, [La-], VO_2, RPE	The positively paced racing strategy was selected by all the swimmers. High [La-] were observed in all trials. A reduced [La-], RPE and unchanged final time observed in the evenly paced trial suggest a less physical strain compared with the positively paced trial and so even pacing could be an alternative pacing strategy for competitive Br swimmers.
Thompson et al. (2004)	To investigate the effects of subtle changes in pace on selected metabolic and kinematic variables, during high-speed Br swimming.	9 regional to national males (23.00 ± 5.00 years)	200m (maximal) 3x 200m (98%, 100% and 102% of maximal pace)	SR, HR, [La-], VO_2, VCO_2, RER, RPE	Swimming at a pace greater than the mean v for a maximal 200m trial caused increases in stroke kinematics and a significant increase in anaerobic metabolism but no differences were found in final time compared to the even-paced trial.
van Houwelingen et al. (2017)	To explore whether the leg-arm coordination within the Br cycle can be influenced with acoustic pacing, and whether the so induced changes are accompanied by changes in dv.	14 regional males and 12 regional females (20.00 ± 3.30 years)	50m (maximal) 10x 50m (70% of maximal pace)	dv, RPE, phase relation	The executed mean phase relation was affected by acoustic pacing and mean executed phase relation increased with increasing imposed phase relation. The average v did not differ for imposed phase relations of 180°, 225° and 270°, with the former being the most efficient coordination among the studied patterns, yielding significantly lower dv.
Vilas-Boas & Santos (1994)	To compare swimming economy between the three Br techniques: the flat style, the undulated style,	3 males and 6 females national level (15.80 ± 2.17 years)	3x 200m (two submaximal and one maximal)	VO_2, [La-], Etot, RC, C	Etot demonstrated a linear function with v. A lower economy was found for the undulated techniques, especially the overwater recovery of the arms.

	and the undulated style with overwater recovery of the arms.				
Vilas-Boas (1996)	To compare dv and swimming economy among three different Br techniques: flat style, undulated style and undulated style with overwater recovery of the arms and to study the relationships between these parameters.	13 national level (15.80 ± 2.17 years)	3x 200m (two submaximal and one maximal) 3x 20m (200m pace)	VO_2, [La-], Etot, RC, C, dv, St	Undulated style with overwater recovery of the arms presented the highest values of dv and was the least economic compared to the other styles. dv and Etot were correlated when interindividual results were considered.
Vilas-Boas et al. (1994)	To evaluate the relationship between Br maximum propulsive impulse per SP, estimated from light trace photographic method, and maximum propulsive tethered force and to evaluate gender differences in maximum Br tethered propulsive force and maximum propulsive resultant impulse during the stroke cycle.	5 top level males (17.60 ± 1.67 years) 7 top level females (14.60 ± 1.72 years)	5 to 10 sec plus 6sec (submaximal and then maximum tethered swimming)	Max propulsive resultant impulses per SP, max propulsive tethered forces, dv, SP	Br technique is characterized by a succession of resistive and propulsive phases, and that is during the acceleration phase associated to the leg kick that is observed the higher positive, or propulsive, horizontal resultant impulse. The second higher positive impulse may be associate to the arm stroke. Male swimmers obtained higher values of maximum tethered force and maximum propulsive horizontal resultant impulse per phase.

Wettengl et al. (2023)	To establish differences in load–velocity profiling, active drag and drag coefficient between three age groups of female swimmers.	33 females (11, 13 and 16 years)	3x 25m (semitethered)	Da, CDa	In breaststroke, maximal load, load normalized to the BM, and Da had large correlations with maximal v in the oldest swimmers, but those correlations were not observed in the 2 younger age groups. Conversely, medium to large negative correlations between CDa and maximal v were detected in the 11- and 13-year-old athletes, but this was not observed in the oldest swimmers.
Xin-feng et al. (2007)	To develop a new device to measure the Da during maximal v based on the assumption of equal useful power output in two cases: with and without a small additional drag.	3 males and 3 females national level	2x 25m (maximal)	Da	v of all participants in the FC was larger than that in the Br, which means that the power expended in the FC is greater than that in the Br, so propulsive efficiency in the FC is greater than that in the Br for a given swimmer. Br coefficient were all greater than the FC coefficients for all swimmers, irrespective of sex.
Zompanakis et al. (2021)	To examine whether breathing frequency in Br, effects swimmers' performance, [La-], and the different swimming efficiency parameters in the 25 and 50m distances.	8 males and 8 females (15.60 ± 3.20 years)	25 and 50m (maximal)	[La-], SR, SL, SI	1 on 1 breathing frequency resulted in a higher [La-] in the 25m.

[La-] - blood lactate concentration; ADTR - acceleration-deceleration time ratio; ALL - arm-leg lag: ALT - percent arm lag time; AnCV - anaerobic critical velocity; AnT - anaerobic threshold; AOD - accumulated oxygen deficit; Ap - frontal area; ApEn - Approximate entropy; AT - anaerobic threshold; Bk – backstroke; Br – breaststroke; Bt – butterfly; C - energy cost; CD - drag coefficient; CDa - active drag coefficient; CDp - passive drag coefficient; CM - center of mass; CRP - continuous relative phase; D - drag force; Da - active drag; Dp - passive drag; dv - intra cycle velocity variation; ep - propelling efficiency; ESP - effective stroke phases; Etot - total energy expenditure; eWPS - effective work per stroke; Fa - average propulsive force; Fatind - fatigue index; Fc - front crawl; Fd - Fractal dimension; Fmax - maximum force; Fmean - mean force; GO - glide or overlap; HR - heart rate; IBFP - index of flat breaststroke propulsion; MSP - maximum swim power; nd - drag efficiency; np - propulsive efficiency; Po - power output; PV - pulmonary ventilation; RC - respiratory coefficient; RER - respiratory exchange ratio; RPE - rating of perceived exertion; S - Frontal surface area; SampEn - sample entropy; SI - stroke index; SL - stroke length; SP - absolute and relative duration of stroke phases; SPT - simultaneous propulsion time; SR - stroke rate; SRT - Simultaneous recovery time; St - Strouhal number; TI – trunk inclination; TG - time gaps; TTG - total time gap; v - swimming velocity; v2 - swimming velocity corresponding to the 2mmol.L-1 threshold; v2 VO_2 - VO_2 elicited at v2; v4 - swimming velocity corresponding to the 4mmol.L-1 threshold; v4VO_2 - VO_2 elicited at v4; VO_2 – oxygen uptake; VC - ventilation coefficient; VCO2 - carbon dioxide expired; VO_2max - maximal O2 uptake; VO_2mean - mean VO_2; vpeak VO_2 - velocity associated to the peak VO_2; Win - mechanical internal work; Wtot- total work.

4. Discussion and implications

This study aimed to synthesize existing literature on kinematics, active drag and energetics determinants of energy cost variability in the breaststroke technique. The main findings were that factors such as stroke rate, stroke length, stroke index, arm-to-leg timing and intra-cyclic variations of velocity were found to significantly impact C in the breaststroke technique. We accepted our hypothesis regarding the influence of kinematic parameter variations on energy cost variability in breaststroke swimming, as well as the role of active drag as key-driver to fluctuations in energy cost in breaststroke swimming.

The quality of eligible studies was assessed using the risk of bias scale developed by Hindle et al. (2019b). One notable finding is that none of the studies reported on how the sample size was determined. This information is important for understanding the sample power computation and the external validity of the findings reported. While some papers demonstrated low bias risk (15 articles), others showed room for improvement, such as addressing the key limitations of the research. Nearly half of the studies acknowledged the importance of considering both sexes in their research (45.2%). However, 34.2% recruited exclusively males, and 6.8% only females, raising concerns about findings' generalizability and applicability across the population. This gender bias limits the ability to draw conclusions about the specific sexes. In addition, it is worth noting that ten studies did not specify the participants' sex. This lack of reporting is a limitation as it precludes a thorough analysis of gender differences and further contributes to the overall gender inequality in the body of knowledge found in the literature.

The predominance of elite and high-level swimmers in the studies reflects a clear emphasis on performance-oriented research. While this focus offers valuable insights into peak performance and training optimization for competitive athletes, it may inadvertently neglect other tiers of the swimming population, such as recreational swimmers or those in developmental stages. Moreover, the lack of studies targeting younger age groups, particularly those under 12 years old, underscores a critical research gap that warrants attention. The prevalence of maximum tests (52.1%) as the preferred protocol indicates a predominant focus on evaluating swimmers' peak performance. Additionally, researchers employed a combination of both maximal and submaximal tests, along with incremental tests. This comprehensive approach enables a thorough assessment of performance across a spectrum of intensities, providing valuable insights into swimmers' capabilities under various exertion levels.

The present review identified three distinct domains of variables: stroke kinematics (including stroke kinematics and coordination parameters), hydrodynamic drag, and energetics. In the forthcoming sections, we will explore each of these variable domains drawing upon existing literature to provide a comprehensive analysis.

Stroke kinematics

In the scope of this review, a significant majority of the included studies (60.3%) focused on reporting kinematic variables. Among them, 26 studies specifically assessed stroke kinematics, such as stroke rate (SR), stroke length (SL), stroke index (SI), and intra-cyclic variations of velocity (dv). Breaststroke swimming consists of propulsive and non-propulsive phases, which affect the swimmer's velocity (v).

a) Arm-to-leg timing

During the arm pull (insweep) and leg kick, the swimmer experiences acceleration and an increase in v, whereas the recovery of the arms and legs and the gliding phase result in deceleration and a decrease in v (D'Acquisto & Costill, 1998; Gourgoulis et al., 2018; Leblanc et al., 2007; Mason, 1989; Vilas-Boas, 1994). There are two peaks associated with the leg and arm propulsive phases and two minimal velocities that correspond to the arm and leg recovery phase and the transition time between the leg and arm propulsive phases, respectively (Gourgoulis et al., 2018). Although the leg propulsive phase produces a steeper increase in v compared to the arm propulsive phase, the latter is equally important, and elite swimmers are able to achieve a better arm-to-leg timing, resulting in a faster v (Leblanc et al., 2005). While the leg propulsive phase produces greater acceleration than the arm propulsive phase, it may not necessarily result in a higher v, as it depends on the swimmer's starting v or their limited ability to perform an effective leg kick (Gourgoulis et al., 2018).

Although the gliding phase (when it occurs) in breaststroke swimming does not generate propulsion, it plays a paramount role in optimizing the swimmer's performance, as adopting a more streamline position in this critical phase enables the swimmers to reduce drag preventing a substantial decrease in v (D'Acquisto & Costill, 1998). Notwithstanding, this transition phase of breaststroke is important for distance covered, and expert swimmers are skilled at adopting a streamlined position during this phase, which can have a significant impact on their swimming economy and overall performance (Leblanc et al., 2005; Takagi et al., 2004). To achieve optimal efficiency during these non-propulsive phases, elite swimmers focus on minimizing drag by using a better-streamlined position and arm-to-leg timing, which can be the key performance discriminator among top performers (Komar et al., 2014; Leblanc et al., 2005).

b) General stroke parameters

At low intensities, when the v slows down, SL increased and SR decreased in breaststroke swimming (Conceição et al., 2013a; Craig & Pendergast, 1979; Leblanc et al., 2007; Gourgoulis and Nikodelis, 2022; Takagi et al., 2004; Thompson et al., 2000, 2004). This is mainly caused by the longer duration of the gliding phase (Chollet et al., 1996). Moreover, breaststroke was the only swimming technique where SL decreased when switching from 200m to 100m paces (Chollet et al., 2004; Craig et al., 1985; Manley, 1992). Within the 200m race laps a greater SR variability for the breaststroke than for the other three strokes was found (Hellard et al., 2008). SR was highly associated with the 50m performance (Strzala et al., 2016) but poorly related with finishing time in the 200m (Thompson et al., 2000). An increase in SR between heats, semi-finals and finals in the 50m breaststroke, was found for men and women. However, only in women, this was related to improved performance (Arellano et al., 2022). Among swimmers who advanced through the rounds, the rise in SR may be a crucial factor, as seen in women. However, in cases where the increase in SR leads to a significant reduction in stroke length (SL), performance deterioration may occur, as evidenced in men (Arellano et al., 2022).

Differences were found between the first and second 50m lap of a 100m breaststroke race (long course meter). In the second 50m, SR was 3.53% faster, and SL and v decreased by 9.73% and 6.04%, respectively (Thompson et al., 2000). Another study found that there was a similar drop in v (7%) but the SR declined noticeably from the first lap to the second and third laps, but rebounded with an increase seen on the final lap, without any difference compared to the initial lap (short course meter) (Oxford et al., 2017). Interestingly, SL remained relatively consistent throughout the swim, with no significant changes observed (Oxford et al., 2017). SI is defined as the product of average v and SL and a proxy of swim efficiency. High SI values are strongly associated with a low energy cost (C) (Costill et al., 1985). The decrease in v in the 100m race was related to the change in the ratio of SL and SR, with a decrease (13%) in SI which indicates that the participants were becoming less efficient as they progressed through the swim (Oxford et al., 2017). Front crawl has the highest SI, followed by backstroke, butterfly and breaststroke (Sánchez & Arellano, 2002).

Between the 50m and the 200m, where mean v decreases, SR is severely reduced while SL increased, more for elite compared to non-elite swimmers (Chollet et al., 1996; Leblanc et al., 2005, 2007; Pai et al., 1984; Takagi et al., 2004; Thompson et al., 2000). In fact, for the same SR, elite female and male swimmers had a greater mean v and SL than non-elite swimmers. So, an elite swimmer can achieve the same or a greater v as a non-elite swimmer, using a different technique with longer SL and lower SR (Leblanc et al., 2005, 2007). Interestingly, there was no significant correlation between SL and SR and clean swimming time (Olstad et al., 2020). This suggests that fast swimmers do not necessarily rely on a long SL, but rather employ their own individual strategies to achieve high clean v (Pai et al., 1984). In addition, SR was not different by gender and performance levels in the 50, 100 and 200m races (Hellard et al., 2008; Takagi et al., 2004).

In the 100m, males presented higher values of SR and v compared to women, but SL values were the same for both male and female swimmers (Oxford et al., 2017; Pai et al., 1984; Seifert & Chollet, 2005). In the 200m, males presented higher SL and v and lower SR compared to women, suggesting that SL was the most important factor influencing performance (Psycharakis et al., 2008). Differences in the ratio of SR and SL may be related to variation in the stroke phases (Chollet et al., 1996; Chollet et al., 1999; Seifert & Chollet, 2005; Soares et al., 1999) or the anthropometric differences, the swimmer's technique and the resultant active drag and v (Kolmogorov & Duplischeva, 1992). Compared to women, men exhibited greater propulsion in both their upper and lower limbs during swimming (Seifert & Chollet, 2005). Male swimmers have also been reported to generate greater mechanical power outputs than females (Kolmogorov et al., 1997).

c) Buoyancy

Women showed a larger reduction in glide duration from the 200m to the 50m pace. Despite these differences, men had a smaller arm glide compared to women (Seifert & Chollet, 2005). No difference between sexes in the time spent in any of the phases of the stroke in the 100m race was found (Oxford et al., 2017) which is not consistent with other study that reported that males spend significantly longer in the propulsive phase of the stroke (Seifert & Chollet, 2005). Female swimmers exhibit greater buoyancy and tend to maintain a more horizontal position when in a static position compared to male counterparts (Leblanc et al., 2010). Correlations between floatation and improved glide were established, highlighting the potential advantages of buoyancy in swimming performance for female athletes. This could be related to a lower drag during this phase of the stroke in female swimmers (Leblanc et al., 2010).

The better buoyancy of females may have decreased their frontal area, thus reducing resistance in the water and promoting a longer and more efficient glide. Additionally, a relationship was found between the SI and hydrostatic lift in female swimmers at a slow pace, highlighting the impact of flotation on stroke efficiency (Leblanc et al., 2010). These findings suggest that buoyancy enhances hydrostatic lift, thereby contributing to stroke effectiveness. The impact of buoyancy on swimming performance may be limited at high velocities, particularly during sprinting, as noted by some researchers (Leblanc et al., 2010). This may be due to a "ceiling effect", whereby the advantages of buoyancy are only held up to a certain range of v, beyond which the benefits diminish. Two possible interpretations can be made: increased v may result in greater lift, which could help to counteract the sinking force experienced by male swimmers, thereby minimizing the benefits of buoyancy. Alternatively, as v increases, there may be changes in arm-leg coordination that lead to a decrease in the glide phase of the stroke. This decrease may reduce the effect of buoyancy on overall swimming performance, as less time is spent in the static phase where buoyancy can have a significant impact (Leblanc et al., 2010).

d) Intra-cyclic variations of velocity

A swimming technique is more economical when the dv is more even for a given average v, because the swimmers do not have to overcome the forces of inertia as well as the hydrodynamic resistance (Kolmogorov et al., 1997). In breaststroke, Vilas-Boas (1996) reported a correlation between the dv and C, signaling that swimmers who exhibit fewer fluctuations are more likely to swim economically. Breaststroke has been defined as the swimming technique with the highest dv and characterized by a two-peak profile (Barbosa et al., 2010b, 2013, 2016, 2017; Xin-Feng et al., 2007). One peak related to arm's actions and the other one to the leg's action (Barbosa et al., 2010b). At times, a third peak was described in the transition between arms and legs´ actions.

It is expected that elite swimmers present a lower dv compared to non-elite swimmers. However, higher values of dv for elite swimmers were reported (Komar et al., 2014; Leblanc et al., 2007). The higher values can be attributed to the fact that elite swimmers achieve higher peak v during the arm propulsive phase, while maintaining nearly the same minimum dv during the recovery phase and that elite swimmers employed a glide coordination style even at sub-maximal v (Leblanc et al., 2009). This introduces a bias when studying the relationship between dv and performance if the v of elite and non-elite swimmers is not at the same % of maximum velocity. Additionally, their drop in v is less pronounced during the leg-arm transition time (glide phase) (Leblanc et al., 2007; Takagi et al., 2004). Therefore, it is important not to decelerate rapidly during the recovery phase, and to keep a relatively higher hip v during the arms' glide phase (Takagi et al., 2004).

Colman et al. (1998) compared the dv of flat and undulation breaststroke styles, and concluded that there was considerably less difference between the maximum and minimum v peaks in the most undulating style than in the lowest flat style. Some swimmers used an overwater arm recovery, described as inefficient as it involves a higher dv related to the trunk drag and a higher energy expenditure (Vila-Boas & Santos, 1994). In addition, an undulated movement of the body was related to the v of the 50m race (Strzala et al., 2015). A swing-like forward immersion during streamlined recovery of arms after their pull and breath, as well as to the lower body movements: straightened legs are then being pulled up to the buttocks, which enhances swinging action called "wave action" (Conceição et al., 2013; Colman et al., 1998; Mason et al., 1989).

e) Power output

In the front crawl, the product of force and v was greater than that in the breaststroke (Xin-feng et al., 2007). This indicates that more power is expended in the front crawl compared to the breaststroke. Since the total useful power output is fixed, it can be concluded that the propulsive efficiency in the front crawl is higher than that in the breaststroke for a given swimmer (Xin-feng et al., 2007). Breaststroke presented the lowest average propulsive force value compared to the other swimming techniques (Hermosilla et al., 2020) as a result of the simultaneous actions of both arms and legs and, consequently, leading to a higher dv (Barbosa et al., 2006). Front crawl showed the higher values of maximum swim power, following by breaststroke, butterfly and backstroke (Hermosilla et al., 2020). In a tethered swimming protocol, breaststroke and butterfly showed both higher and lower force production values compared to front-crawl and backstroke (Morouço et al., 2011). Notably, breaststroke swimmers recorded the highest tethered swimming force values, and the v of a 50m breaststroke was found to have the highest correlation with maximum force production (Morouço et al., 2011). In addition, maximum propulsive tethered force and maximum propulsive horizontal resultant impulse per breaststroke phase, were higher in male than in female swimmers (Vilas-Boas, 1994).

f) Complexity and predictability

Approximate entropy (ApEn) and sample entropy (SampEn) provide insight of the randomness of the inter-cyclic variations over a time-series. The lower its values, the higher the predictability of a time-series (Pincus, 1991). Fractal dimension (Fd) describes the properties of a system that demonstrates fractality or other properties that do not change over time and/or space. The higher the Fd, the more complex the time series is (Bravi et al., 2011). Breaststroke showed the highest value of Fd, the second lowest values of ApEn and the lowest value of SampEn comparing to the other swimming techniques. So, comparing to the four competitive techniques, breaststroke has a more complex but more predictable swimming pattern (Barbosa et al., 2016, 2017; Bartolomeu et al., 2018).

Coordination parameters

A total of 18 articles included in this review reported coordination parameters, emphasizing their significance within the research. Additionally, two papers investigated both coordination and energetics, providing a comprehensive examination of these interrelated aspects. In breaststroke, a change in v is related to an increase in limbs´ v, a change in the arm-leg coordination and the change of the relative duration of the separate stroke phases (Leblanc et al., 2007; Oxford et al., 2017; Takagi et al., 2004). With increasing v, a greater arm and leg propulsion and decreased arm and leg glide phases has been described (Chollet et al., 1996, 1999, 2004; Seifert & Chollet, 2005).

Relative percentages of arm and leg recoveries presented higher values in the 50m compared to the 200m pace (Chollet et al., 2004; Leblanc et al., 2005). Conversely, the absolute duration of the arm recovery was reported to become higher as the event distance increased (Soares et al., 1999). A longer arm recovery in the fastest pace may be explained by the need to catch the water before the arms are pulled out (Chollet et al., 2004). During the breaststroke, the leg recovery phase is considered the most significant braking phase. As swimming v increases, so does the active drag, particularly during this phase, which results in a need for longer leg recovery time (Leblanc et al., 2005; Chollet et al., 2004). Despite this, the distance covered during the leg and arm recoveries and during the absolute arm-stroke was not influenced by race pace in either elite or non-elite swimmers (Leblanc et al., 2007; Olstad et al., 2017).

In the 100m race, between laps the participants showed no change in the amount of time spent in the propulsive phases of the stroke or the recovery phases of the stroke (Oxford et al., 2017). In addition, the elbow push and leg insweep remained stable throughout the 50, 100, and 200m paces (Chollet et al., 2004). This can explain why the SL did not change during the 100m swim. In addition, even with increasing effort, the absolute duration and distance during the knee extension phase remained similar (Olstad et al., 2017). This suggests that the swimmers maintained a strong kick even at lower effort levels, or it could be attributed to the change in knee angle, which provided a better mechanical advantage. Specifically, the swimmers pulled their feet higher up towards the buttocks, resulting in a longer distance to travel and increased force on the water. Moreover, this change in knee angle also aided to a better upper body streamline at the beginning of this phase (Olstad et al., 2017).

Between elite and non-elite swimmers, differences in swimming v did not correspond with differences in arm propulsion duration, which might suggest that elite swimmers had a better propelling efficiency (Leblanc et al., 2005, 2009). For instance, the duration of the insweep phase was longer in the non-elite male and female groups. These swimmers make a common technical mistake by dropping their elbows back and by pushing down with their arms which causes drag and is time consuming (Leblanc et al., 2005). In addition, the outsweep phase was shorter in non-elite swimmers as they did not move out their hands to the side enough. By doing so, they tended to push down against the water with a dropped elbow position (Leblanc et al., 2005).

Elite swimmers tend to have longer duration of the leg recovery than non-elite counterparts, but a shorter duration of the arm recovery (Leblanc et al., 2005, 2009). The longer arm recovery of non-elite swimmers may be linked to a longer breathing time of the non-elite swimmers. In fact, a negative correlation between the arm recovery and v was found, showing that a slow transport of the upper limbs after the end of propulsion production or prolonging their transfer in this phase is unfavorable for achieving higher swim v (Strzala et al., 2014). In addition, elite swimmers presented a lower leg glide phase duration compared to non-elite swimmers. Conversely, the arm glide phase did not differ between the two groups (Leblanc et al., 2005) and results showed that the experts and recreational swimmers spent the same time with arms and legs out-stretched, therefore the same relative duration of the glide (Komar et al., 2014). However, for expert swimmers, the glide phase corresponds to an effective in-phase coupling of limbs movement (i.e., simultaneous extension of legs and arms), and varying with the v (Komar et al., 2014).

In the researches by Leblanc et al. (2005; 2007), the effective propulsion times of the elite groups were longer and their effective glide times shorter than non-elite swimmers. Indeed, the ability to swim fast on the surface was positively associated with the percentage time of propulsion generation and the non-propulsive phase (leg recovery of the legs, including gliding) was negatively correlated to v (Strzala et al., 2015). The adaptation to v mostly comes from a regulation of the glide time (Komar et al., 2014). This strategy enables experts to maintain effectiveness of propulsions and glide, but also leads to higher dv. Nevertheless, both experts and recreational swimmers exhibited greater dv during the low v condition, mainly due to higher deceleration related to greater time spent gliding, which is in agreement with a previous study (Leblanc et al., 2007). A study on deterministic models in competitive swimming (Barbosa et al., 2010a), showed that high-level swimmers are characterized by lower inter limb coordination total time gap (TTG - the sum of the different time gaps between propulsive movement of the upper and lower limbs) (Chollet et al., 2004; Leblanc et al., 2005, 2009). In fact, TTG showed a significant interplay both with v of the 50m race and SR (Strzala et al., 2015). Elite breaststrokers are able to lower the percentage of non-propulsive phases in cycle movement (which means longer periods of effective propulsion) (Leblanc et al., 2009).

Recreational swimmers tend to perform arm recovery and leg kick simultaneously, characterized by the extension of both pairs of limbs at the same time (Leblanc et al., 2009). This produces a movement that resembles an “accordion-like” motion, as the propulsion of one pair of limbs is thwarted by the underwater recovery of the other pair of limbs (Seifert et al., 2011). Competitive swimmers organize their cycle by doing the propulsion of one pair of limbs while the other pair of limb’s glide in a hydrodynamic position (i.e., extended) and synchronize both recoveries of the arms and legs (Komar et al., 2014; Seifert et al., 2011). Given that both arm and leg recoveries are underwater and thus cause high drag, they should be synchronized (Chollet et al., 2004). The simultaneous recovery time tends to increase with increasing distance (Takagi et al., 2004).

There are three general styles of breaststroke timing, i.e. overlap, continuous and glide. With increasing v, an exaggerated overlap time led the swimmers to start their arm propulsion while their leg kick was still accelerating their body, leading to a higher active drag (Leblanc et al., 2009; Oxford et al., 2017). Elite swimmers, on the other hand, start the arm propulsion earlier after the leg extension and the squeezed leg position. This reduces the propulsion gap and motor gap between the leg insweep and the arm catch, resulting in reduced v fluctuations (Leblanc et al., 2005; Seifert & Chollet, 2005). By utilizing overlap timing and better body position, the period of deceleration can be reduced and higher minimum linear body v before the propulsive phase generated from the arm pull established, and sprinting ability enhanced (D'Acquisto & Costill, 1998). The flat breaststroke is characterized by this coordination style. Research has shown that the flat style, with its smaller v fluctuations, is more economical than the undulated breaststroke with over-water arm recovery (Vilas-Boas, 1996). So, by beginning arm propulsion earlier, these swimmers anticipated and limited body deceleration (Craig et al., 1988; Maglischo, 1993) and were also capable of producing a higher SR (Chollet et al., 2004; Leblanc et al., 2005; Takagi et al., 2004).

Competitive swimmers exploit a gliding coordination style at slower v, while elite swimmers employed a glide coordination style even at sub-maximal v (Leblanc et al., 2009). By incorporating a gliding phase into their swimming technique, competitive swimmers are able to take advantage of the propulsive force generated by their leg kick, since their arms are already in a well-aligned and recovered position. This contrasts with recreational swimmers, who typically lack a gliding phase and may experience reduced efficiency in their strokes and leg propulsive action (Leblanc et al., 2009; Seifert et al., 2011).

Hydrodynamic drag

There is limited amount of data available on the active drag (Da) in breaststroke swimming technique. Only five articles reported hydrodynamic drag and one paper reported both drag and energetics. The breaststroke technique exhibits higher values of Da and frontal area compared to other swimming techniques (Gatta et al., 2015; Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997, 2021; Xin-feng et al., 2007). In addition, breaststroke exhibits approximately twice the amount of Da compared to the passive drag, a feature that is not as prominent in other swimming techniques (Gatta et al., 2015).

Numerous experiments have been conducted to determine Da in swimming. For instance, early measurements involved indirect calculations of Da based upon changes in oxygen consumption with additional drag loaded onto the swimmer (Di Prampero et al., 1974). Another approach involved using the Measuring Active Drag (MAD) system, which directly measures Da (Hollander et al., 1986). The MAD system is widely regarded as the gold standard for assessing Da, however, it is limited to evaluating the front crawl technique. The velocity perturbation method (VPM) was introduced as a method that allows for the measurement of Da in all four swimming techniques (Kolmogorov & Duplishcheva, 1992). The VPM relies on the assumption that a swimmer can generate the same maximum power output during two bouts - one towing an additional buoy with a known resistance (Kolmogorov & Duplishcheva, 1992). Xin-feng et al. (2007) developed a new device based on the same assumption as Kolmogorov & Duplishcheva (1992) and was able to measure Da in breaststroke. Finally, Gatta et al. (2015), estimated Da based on the average frontal area values measured during a complete stroke cycle in each swimming technique.

Energetics

Approximately 33% of the studies included in this review focused on reporting bioenergetical parameters, such as lactate concentration ([La-]), oxygen uptake (VO_2), C and energy expenditure. Breaststroke has consistently been described as the swimming technique with the highest C compared to other swimming techniques (Barbosa et al., 2006; Capelli et al., 1998; Holmér, 1974a; Kolmogorov et al., 2021). The C and Etot in breaststroke exhibit a linear increase across a range of v (Capelli et al., 1998; Vilas-Boas & Santos, 1994). While theoretical models suggest that energy output should vary with the cube of v, observed results may be attributed to variations in efficiency, drag, and synchronization across a range of v (Vilas-Boas & Santos, 1994). The substantial energy expenditure required to accelerate the body during the push phase likely accounts for this discrepancy. Such compensation is necessary to counterbalance the v loss experienced in the non-propulsive phase of the stroke (Capelli et al., 1998).

SF and SL have been found to influence C in breaststroke. Increasing SF results in higher energy expenditure, even when controlling for v. Conversely, increasing SL leads to a significant decrease in C, independent of v (Barbosa et al., 2008). Increasing the duration of the gliding phase after the kick action, leads to an increase in the SL. Consequently, there will be a decrease in C (Barbosa et al., 2008). The freely chosen inter-limb coordination pattern in breaststroke minimizes C, suggesting that swimmers can optimize their coordination to reduce energy expenditure (Seifert et al., 2014). Additionally, breaststrokers exhibit higher coordination flexibility compared to front crawlers under constrained coordination conditions, without significant extra C when a "minimal glide" is imposed (Seifert et al., 2014).

While breaststroke exhibits higher C, it demonstrates lower v compared to front crawl for the same metabolic power (Kolmogorov et al., 2021). Breaststroke also presents lower values of lactate concentration ([La-]), v at the anaerobic threshold and anaerobic critical v compared to other swimming techniques (Carvalho et al., 2020; Holfelder et al., 2013; Marinho et al., 2011). However, other ventilatory and metabolic parameters, including

VO_2max, are similar between breaststroke and front crawl during maximal swimming, suggesting comparable physiological demands (Lomax et al., 2022). Velocity at ventilatory threshold was slower during breaststroke comparing to front crawl (Lomax et al., 2022). It is worth noting that while increasing SR and decreasing SL can result in higher v, it also leads to increased [La-] (Psycharakis et al., 2008). Increasing the SR in breaststroke swimming can lead to an increase in the C. This increase is caused by the loss of energy due to increasing resistance during rapidly performed non-propulsive movements of the leg recovery phase (Chollet et al., 2004; Manley, 1992; Vorontsov & Rumyantsev, 2000) or/and reducing the amount of glide time between each cycle can eliminate the brief period of rest.

It has been reported that C correlates negatively with performance, but results for breaststroke do not support such data, since C was not included in any of the regression models that were found (Reis et al., 2010). Another commonly reported association in the literature is a positive correlation between peak [La-] and performance (Bonifazi et al., 1993). However, support for such a relationship was not found in a study (Reis et al., 2010).

The 200m breaststroke event presents a significant anaerobic contribution (Conceição et al., 2013a; Capelli et al., 1998; Thompson, 1998). In fact, the 200m final resulted in a greater absolute [La-] compared to the 100m final, suggesting a higher anaerobic demand in the longer race (Thompson, 1998). Interestingly, when the 200m trial was performed with an even pace, a reduced [La-] was observed, indicating a lower physical strain compared to a positively paced trial (Thompson et al., 2003, 2004). The v in the 200m race and the v during turns have been found to correlate with the leg peak oxygen consumption measured during a cycling test (Strzala et al., 2015).

It has been shown that peak VO_2 is a reliable predictor of performance in swimming (Chatard et al., 1990; Costill et al., 1985). Surprisingly, in the case of the 100m breaststroke event, a negative correlation was observed between peak VO_2 and the athletes' best performance of the season (Reis et al., 2010). This suggests that successful breaststroke swimmers may possess a larger anaerobic capacity, allowing them to meet the demands of the stroke and the event. Troup (1992) also found a relationship between certain anaerobic variables and breaststroke performance, further supporting this notion. Furthermore, in the 100m breaststroke, a negative correlation was observed between the VO_2 elicited at a v corresponding to the 4 mmol. l^{-1} lactate threshold and peak VO_2 in relation to performance. This indicates that higher levels of aerobic ability may hinder optimal performance in this event (Reis et al., 2010). Given the event's short duration and high intensity, it is likely that the influence of anaerobic ability outweighs the importance of extremely high levels of aerobic capacity.

Limitations and research gaps

In the present review, none of the included studies reported on participants under 12 years of age. This suggests a gap in research concerning younger swimmers and signals a need for future studies catering this age group. Understanding the determinants of energy cost in breaststroke swimming for younger swimmers is important, considering their unique physiological and developmental characteristics.

Additionally, the variation in methodologies, measurement techniques, and terminology used across different studies can make it challenging to compare and generalize findings. Establishing standardized methodologies and terminology would enhance the reliability and comparability of research in this field. For instance, the information highlights various coordination parameters such as arm-leg coordination, relative duration of stroke phases, and coordination styles. However, there may be a lack of standardized definitions and measurement techniques for these parameters. Establishing consistent definitions and measurement protocols would enhance the comparability of research findings and facilitate a deeper understanding of coordination patterns.

Future studies should also address the scarcity of available data on the active drag associated with the breaststroke swimming technique. This lack of data limits our understanding of the specific characteristics and factors influencing active drag in breaststroke. In addition, there is a need for multidisciplinary studies that do not focus on only one scientific domain, as only approximately 18% (12 articles) of the papers described associations between domains.

5. Conclusions

Findings revealed that stroke kinematics, including SR, SL, SI, and dv, play a crucial role in influencing C in breaststroke swimming. Moreover, the analysis highlighted the importance of propulsive and non-propulsive phases, arm-to-leg timing and buoyancy of breaststroke.

With increasing v in breaststroke, a greater arm and leg propulsion and decreased arm and leg glide phases has been described. Relative percentages of arm and leg recoveries also presented higher values at higher v. Non-elite swimmers present a higher duration of the insweep phase and a shorter outsweep phase of the upper limbs. The effective propulsion times of the elite groups were longer and their effective glide times shorter than non-elite swimmers. Recreational swimmers tend to perform arm recovery and leg kick simultaneously, competitive swimmers exploit a gliding coordination style at slower v, while elite swimmers employed a glide coordination style even at sub-maximal v.

The breaststroke technique exhibits higher values of active drag, frontal area, energy cost and lower velocity compared to other swimming techniques. Overall, this synthesis of literature highlights the holistic nature of C in breaststroke swimming and it provides a comprehensive understanding of the determinants influencing energy cost.

Appendix

Table 3 - Search strategies for each database.

Scopus	[All fields] (Swimmers* OR Competition* OR Human* OR Athlete* OR Young* OR Adolescent* OR Female* OR Male*) AND (Breaststroke) AND (“Energy cost” OR “Energy expenditure” OR “Metabolic power” OR “Active drag” OR Kinematic OR “Intra cyclic velocity” OR “Intracyclic velocity” OR “Speed fluctuation” OR “Stroke length” OR “Stroke distance” OR “Stroke rate” OR “Stroke frequency” OR “Stroke index”)
PubMed	(Swimmers* OR Competition* OR Human* OR Athlete* OR Young* OR Adolescent* OR Female* OR Male*) AND (Breaststroke) AND ("Energy cost" OR "Energy expenditure" OR "Metabolic power" OR "Active drag" OR Kinematic OR "Intra cyclic velocity" OR "Intracyclic velocity" OR "Speed fluctuation" OR "Stroke length" OR "Stroke distance" OR "Stroke rate" OR "Stroke frequency" OR "Stroke index")
Web of Science	ALL= (Swimmers* OR Competition* OR Human* OR Athlete* OR Young* OR Adolescent* OR Female* OR Male*) AND (Breaststroke) AND (“Energy cost” OR “Energy expenditure” OR “Metabolic power” OR “Active drag” OR Kinematic OR “Intra cyclic velocity” OR “Intracyclic velocity” OR “Speed fluctuation” OR “Stroke length” OR “Stroke distance” OR “Stroke rate” OR “Stroke frequency” OR “Stroke index”)
EBSCOhost	[All databases] TX (Swimmers* OR Competition* OR Human* OR Athlete* OR Young* OR Adolescent* OR Female* OR Male*) AND TX Breaststroke AND TX (“Energy cost” OR “Energy expenditure” OR “Metabolic power” OR “Active drag” OR Kinematic OR “Intra cyclic velocity” OR “Intracyclic velocity” OR “Speed fluctuation” OR “Stroke length” OR “Stroke distance” OR “Stroke rate” OR “Stroke frequency” OR “Stroke index”)

Table 4 - Quality assessment of included studies.

Authors	1.1.	1.2.	1.3.	2.1.	2.2.	2.3.	2.4.	3.1.	3.2.	3.3.	3.4.	4.1.	4.2.	4.3.	4.4.	4.5.	**Total:**
Arellano et al. (2022)	x	x	x	x		x		x	x	x	x	x	x		x		12
Barbosa et al. (2006)	x	x						x	x	x	x	x	x				8
Barbosa et al. (2008)	x	x			x			x	x	x	x	x	x	x			10
Barbosa et al. (2010)	x	x			x			x	x	x	x	x	x		x		10
Barbosa et al. (2013)	x	x	x	x	x	x		x	x	x	x	x	x	x			13
Barbosa et al. (2016)	x	x	x					x	x	x	x	x	x	x			10
Barbosa et al. (2017)	x	x	x	x				x	x	x	x	x	x		x		11
Bartolomeu et al. (2018)	x	x	x	x				x	x	x	x	x	x		x	x	12
Capelli et al. (1998)	x	x			x			x	x	x	x	x	x				9
Carvalho et al. (2020)	x	x	x		x			x	x	x	x	x	x		x		11
Chollet et al. (1996)	x	x								x	x	x	x				6
Chollet et al. (2004)	x	x			x			x		x	x	x	x				8
Colman et al. (1998)	x	x						x				x	x				5
Conceição et al. (2013a)	x	x			x			x	x	x	x	x	x				9
Conceição et al. (2013b)	x	x			x			x	x	x	x	x	x				9
Craig & Pendergast (1979)	x	x						x		x	x	x	x				7
di Prampero et al. (2008)	x				x			x				x	x				5
Gatta et al. (2015)	x	x			x			x		x	x	x	x			x	9
Gourgoulis & Nikodelis (2022)	x	x	x		x			x		x	x	x	x			x	10
Gourgoulis et al. (2018)	x	x	x		x			x		x	x	x	x		x		10
Hellard et al. (2008)	x	x	x		x			x		x	x	x	x				9
Hermosilla et al. (2020)	x	x						x	x			x	x		x		7
Holfelder et al. (2013)	x	x		x	x	x		x	x	x	x	x	x				11
Holmér (1974a)	x	x			x			x				x	x		x		7
Holmér (1974b)	x	x			x			x	x			x	x		x		8
Kolmogorov & Duplishcheva (1992)	x	x			x			x				x	x				6
Kolmogorov et al. (1997)	x	x				x		x	x	x	x	x	x				9
Kolmogorov et al. (2021)	x	x	x		x			x	x			x	x		x		9
Komar et al. (2014)	x	x	x		x			x	x	x	x	x	x		x		11
Lauer et al. (2015)	x	x			x			x	x	x	x	x	x		x		10
Leblanc et al. (2005)	x	x			x			x	x	x	x	x	x				9
Leblanc et al. (2007)	x	x	x		x			x		x	x	x	x				9
Leblanc et al. (2009)	x	x	x		x			x	x	x	x	x	x				10
Leblanc et al. (2010)	x	x	x		x			x	x	x	x	x	x				10
Lomax et al. (2022)	x	x	x		x			x	x	x	x	x	x		x		11
Marinho et al. (2011)	x	x			x			x		x	x	x	x				8
Mason (1989)	x	x						x				x	x				5

Morouço et al., 2011	x	x			x			x		x	x	x	x		x	9
Oliveira et al. (2016)	x	x	x		x			x	x	x	x	x	x			10
Olstad et al. (2017)	x	x			x			x	x	x	x	x	x		x	10
Olstad et al. (2020)	x	x	x		x			x	x	x	x	x	x		x	11
Oxford e al. (2017)	x	x	x		x			x	x	x	x	x	x		x	11
Pai et al. (1984)	x	x								x	x	x	x		x	7
Psycharakis et al. (2008)	x	x			x			x	x	x	x	x	x		x	10
Reis et al. (2010)	x	x	x		x			x	x	x	x	x	x		x	11
Sánchez & Arellano (2002)	x	x						x	x		x	x	x			7
Seifert & Chollet (2005)	x	x	x		x			x		x	x	x	x			9
Seifert et al. (2010)	x	x	x		x			x	x	x	x	x	x			10
Seifert et al. (2011)	x	x			x			x	x	x	x	x	x			9
Seifert et al. (2014)	x	x	x		x			x	x	x	x	x	x		x	11
Sharp & Costill (1989)	x	x						x	x	x	x	x	x		x	9
Staniak et al. (2016)	x	x			x			x			x	x	x		x	8
Stosic et al. (2022)	x	x	x					x	x	x	x	x	x		x	10
Strzala et al. (2013)	x	x			x			x		x	x	x	x		x	9
Strzala et al. (2014)	x	x			x			x	x	x	x	x	x	x		10
Strzala et al. (2015)	x	x	x		x			x	x	x	x	x	x	x		11
Strzala et al. (2016)	x	x	x		x			x	x	x	x	x	x	x		11
Takagi et al. (2004)	x	x						x	x	x	x	x	x		x	9
Thompson (1998)	x	x			x			x				x	x			6
Thompson et al. (2000)	x	x						x		x	x	x	x			7
Thompson et al. (2003)	x	x			x			x	x	x	x	x	x			9
Thompson et al. (2004)	x	x			x			x	x	x	x	x	x			9
van Houwekingen et al. (2017)	x	x			x			x		x	x	x	x		x	9
Vilas-Boas & Santos (1994)	x	x			x			x	x	x	x	x	x			9
Vilas-Boas (1996)	x	x			x			x	x	x	x	x	x			9
Vilas-Boas et al. (1994)	x	x			x			x		x	x	x	x		x	9
Xin-feng et al. (2007)	x	x						x				x	x		x	6
Zompanakis et al. (2021)	x	x			x			x		x	x	x	x			8

Chapter 3. Does breathing every two cycles improve the breaststroke energy cost?

Miriam Alves[1], Ana Sofia Monteiro[1,2,3], Ricardo J. Fernandes[1,2,3], Tiago M. Barbosa[4,5], João Paulo Vilas-Boas[1,2,3]

[1] Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D);

[2] Porto Biomechanics Laboratory (LABIOMEP-UP);

[3] Faculty of Sport, University of Porto, 4099-002 Porto, Portugal;

[4] Department of Sport Sciences, Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal;

[5] Research Centre for Active Living and Wellbeing (LiveWell), Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal

Alves, M., Monteiro, A. S., Fernandes, R. J., Barbosa, T. M.; Vilas-Boas, J. P. (2025). Does breathing every two cycles improve the breaststroke energy cost? *International Journal of Sports Medicine.* DOI: 10.1055/a-2657-9181

Abstract

World Aquatics rules require only part of the swimmer's head to break the surface each breaststroke cycle. We aimed to assess the impact of breathing every one or two cycles in breaststroke on energy cost (C) and related bioenergetic variables. Fifteen swimmers completed a six-week intervention to learn the new breathing pattern, followed by a 5 × 200 m step test (0.05 $m \cdot s^{-1}$ increments, 30 s rest) in both patterns. Oxygen consumption ($\dot{V}O_2$) and blood lactate ($[La^-]$) were measured to calculate energy expenditure ($\dot{E}_{tot}$) and C. Linear and exponential regressions were computed between $\dot{E}_{tot}$ and velocity. Paired t-tests and ANCOVA were applied, controlling for World Aquatics points and age. $[La^-]$ peak, $\dot{V}O_2$ peak, $\dot{E}_{tot}$, and C were lower at some intensities when breathing every cycle. Adjusted analyses showed higher $\dot{E}_{tot}$ with breathing every two cycles at steps one, two, and five. Linear and exponential regressions showed strong associations for both breathing patterns ($r^2 = 0.74$ vs 0.72, respectively). Individual regressions showed similar patterns in some swimmers, while others differed. Breathing every two cycles elicited higher bioenergetic responses at steps one, two, and five, and did not prove effective during incremental 200 m efforts when compared to the traditional breathing pattern.

KEY-WORDS: OXYGEN COMSUPTION; LACTATE CONCENTRATION; PERFORMANCE

1. Introduction

In competitive swimming, a low number of breathing cycles should be employed at short-time high-intensity events to optimize performance (by minimizing drag and keeping an optimized streamlined position). It has been demonstrated that breath-holding in front crawl results in faster 25 m times compared to higher breathing frequencies (e.g., Pedersen & Kjendlie, 2006). Also, the increase in swimmers' trunk inclination in butterfly while inhaling disrupts the body alignment, potentially increasing drag (Alves et al., 1999; Hahn and Krug, 1992; de Jesus et al., 2012) and shortening the relative duration of the upper limb propulsion phase (Seifert et al., 2010). Many studies have examined the effects of controlled breathing frequency on swimming related bioenergetical variables (e.g. Kapus et al., 2003), such as blood lactate concentrations ($[La^-]$) and heart rate, but exclusively focused on the front crawl technique and yielded mixed findings. It was found no impact of a controlled breathing frequency on $[La^-]$ in 400 m and 100 yards maximal bouts, in the incremental 7 x 200 m test and when employing the tethered and free-swimming methodologies (Key et al., 2014; Murlasits et al., 2023; West et al., 2005). Conversely, it was observed that controlled breathing frequency caused lower heart rate and ventilatory responses (West et al., 2005; Key et al., 2014) even if no alteration in carbon dioxide production or respiratory exchange ratio was evident (Dicker et al., 1980).

Among the four conventional swimming techniques used in competitive events, breaststroke is characterized by its unique features due to distinct mechanics. It presents a larger frontal area and active drag values comparing to other techniques (Gatta et al., 2015; Kolmogorov et al., 1997; Xin-Feng et al., 2007) and is the one with the highest energy cost of locomotion (C) (Barbosa et al., 2006; Capelli et al., 1998; Kolmogorov et al., 2021). Breaststrokers typically breathe in every cycle of the upper and lower limbs, emerging their head and part of the torso above the water surface, affecting their streamlined position and compromising the overall propulsion. In a 25 m breaststroke bout, it was evidenced that breathing every cycle led to higher $[La^-]$, whereas breathing every three cycles allowed to swim faster (Zompanakis et al., 2021). However, no differences in active drag values were observed between breathing every cycle vs two cycles during 25 m maximal bouts (Alves et al., 2024).

In accordance with the World Aquatics rules (effective from November 9, 2024), swimmers should have a part of their head breaking out the water surface during each complete breaststroke cycle, not being necessary to fully lift their heads and torsos out of the water at every cycle. Considering that an increased frontal area results in higher C (Chatard et al., 1990; Kjendlie et al., 2004) and that drag is directly proportional to the projected body area in the direction of displacement (Kjendlie & Stallman, 2008; Pendergast et al., 2005; Vilas-Boas et al., 2010), it is expected that, by minimizing the number of non-propulsive body movements (like the one that occurs allowing the inspiratory action), swimmers can effectively decrease drag and, consequently, C. By reducing the unnecessary body movements associated with breathing, swimmers may reduce the resistance to the direction of motion and expend less energy, leading to enhanced efficiency and improved performance.

Acknowledging the existence of a specific gap both in scientific research and practical application in training settings regarding the influence of the selected breathing pattern in swimming (particularly regarding breaststroke performance), we have compared breaststroke breathing every cycle vs two cycles at a long spectrum of intensities considering swimmers age and World Aquatics points as potential confounding variables. We have focused particularly on C and associated bioenergetic variables and hypothesized that by using a lower number of breathing actions in consecutive cycles would result in less C compared to the traditionally used breathing pattern. As secondary objective, energy expenditure ($\dot{E}_{tot}$) values were extrapolated to higher velocities than those directly studied, specifically to velocities corresponding to 50 and 100 m race paces for each breathing pattern.

2. Methods

Participants

Fifteen swimmers (nine females and six males) of 16.7 ± 5.5 vs 15.9 ± 3.0 years old and with 49.4 ± 10.1 kg vs 57.0 ± 11.6 kg of body mass and 158.9 ± 9.2 cm vs 169.3 ± 10.1 cm of height, were recruited from local swimming teams. Their competitive level was determined according to the individual 25 m pool 100 m breaststroke best performance, i.e., 355.7 ± 97.8 vs 376.2 ± 122.6 World Aquatics points (as established by World Aquatics) for females and males (respectively). The inclusion criteria were: (i) having, at least, five years of competitive swimming experience; (ii) participating at regional competitive level events (or higher); and (iii) do not presenting any injury in the six months prior to the evaluations. The current research was approved by the local ethics committee and followed the rules of the Declaration of Helsinki (2000). Swimmers were informed of the experimental procedures, potential risks and benefits of the study, and gave their written consent to participate (or parents when swimmers were minors).

Intervention program

After the main competition of the first training season macrocycle, during the transition phase leading to the second macrocycle, swimmers were engaged in an intervention program lasting six weeks and consisting of 18 sessions (three sessions per week of 20 min each) in a 25 m indoor swimming-pool (adapted from Chainok et al., 2023). A video with the new breathing pattern (breathing every two upper and lower limbs cycles) was watched in the first session, with swimmers being allowed to self-explore during training session. The coach's feedback progressively changed from analytical to global interventions during the first week and, in the following two weeks, swimmers underwent three sessions with low intensity and increasing volume. An increase in the training intensity was prescribed in the fourth and fifth weeks and the training load alternated between volume and intensity in the last week. Swimmers were assigned to train under this program to progressively increase the practice difficulty, with appropriate challenges beyond their skill levels, facilitating skill learning (Guadagnoli & Lee, 2004; Dadashi et al., 2013), disposing of specific coaching feedback regarding swimming technical aspects.

Data collection

Pre and post the intervention program, swimmers performed a series of 3 x 25 m breaststroke maximal bout breathing every two cycles (with 3 min rest in-between). Swimmers were considered to be familiarized with the new breathing pattern if the times did not differ between the repetitions in the post intervention program test and if they were able to perform the required breathing pattern. Then, one week after the end of the program, swimmers performed an incremental intermittent protocol twice (once with breathing every cycle and once every two cycles), in randomized order. Each session consisted of 5 × 200 m breaststroke with 0.05 $m \cdot s^{-1}$ velocity increments and 30 s rest intervals, separated by 48 hours (adapted from Fernandes et al., 2010; Carvalho et al., 2020; Monteiro et al., 2020). The velocity of the last step was individually calculated according to the swimmers' best performance in the 200 m breaststroke at the moment, eliciting a starting velocity of ~0.3 $m \cdot s^{-1}$ slower than their target time. Swimmers initiated each step in-water and followed a pacer (Pacer2Swim; KulzerTEC, Santa Maria da Feira, Portugal) with flashing lights placed on the bottom of the pool (Fernandes et al., 2012; Zacca et al., 2019). They were advised to reduce gliding during the starts and turns to keep swimming velocity as constant as possible regarding the pacer lights (Gonjo et al., 2021).

Gas exchange was measured breath-by-breath using a portable gas analyser (K5, Cosmed, Rome, Italy) during 2 min at rest, at 30 s intervals between steps, and during the 5 min immediately following the completion of the protocol. The device was calibrated before each experiment according to manufacturer instructions using ambient air against known concentrations (16% O_2 and 5% CO_2) and a 3 L syringe (Fernandes et al., 2012; Sousa et al., 2014). Immediately after completing each 200 m step, swimmers were instructed to exhale into a breathing mask as soon as it was fitted over their mouth and nose, minimizing the time delay between the end of exercise and the first respiratory measurement (Monteiro et al., 2020, Zacca et al., 2022). Participants remained still in water (immersed up to the shoulders in an upright position) allowing the collection of 5 μL capillary blood samples from the fingertip at rest, immediately after each step and at the 1, 3, 5 and/or 7 min after the protocol until the [La^-] peak values were identified (Zacca et al., 2019; Carvalho et al., 2020; Wakayoshi et al., 1993) using a Lactate Pro2 (Arkay, Inc. Kyoto, Japan).

Bioenergetic variables

The $\dot{V}O_2$ peak values for each step of the incremental protocol were determined by backward extrapolation to time zero of recovery using both linear and exponential regressions applied to the first 20 s of recovery data (Lavoie et al., 1983; Monteiro et al., 2020; Zacca et al., 2022). $\dot{E}_{tot}$ per step was calculated using the equation (1) $\dot{E}_{tot} = \dot{V}O_2 + \beta\dot{L}a_b + PCr\,(1 - e^{-t/\tau})$, where $\dot{V}O_2$ is the aerobic contribution (calculated from the time integral of the net $\dot{V}O_2$ vs time), $\beta\dot{L}a_b$ is the net accumulation of [La^-] after exercise, β is the 2.7 mL $O_2 \cdot mM^{-1} \cdot kg^{-1}$ energy equivalent for [La^-] accumulation in blood (Fernandes et al., 2005; Sousa et al., 2014; Thevelein et al., 1984), PCr is the phosphocreatine representing the anaerobic alactic contribution, t is the time duration, τ is the 23.4 s time constant of PCr splitting at work onset and M is the body mass. C was calculated as the ratio between $\dot{E}_{tot}$ and velocity, respiratory frequency was assumed as the number of breaths per minute and respiratory quotient was determined as the ratio of carbon dioxide produced to $\dot{V}O_2$ (Vilas-Boas and Santos, 1994; Fernandes et al., 2005; Figueiredo et al., 2013a).

Although theoretical models suggest that energy output should vary with the cube of velocity, the $\dot{E}_{tot}$ and C in breaststroke exhibit a linear increase across a range of swimming velocities (Capelli et al., 1998; Vilas-Boas and Santos, 1994). This might result from changes in efficiency, drag and coordination between propulsive actions across different velocities (Vilas-Boas & Santos, 1994; Figueiredo et al., 2013b; Fernandes et al., 2024). This discrepancy could be explained by a potentially more pronounced increase in efficiency relative to drag as swimming velocity increases (Vilas-Boas & Santos, 1994; Zacca et al., 2022). Therefore, we have computed linear and exponential regression equations between $\dot{\mathrm{E}}_{\mathrm{tot}}$ and velocity for the entire sample and for each swimmer to determine which model provided the best fit. Then, $\dot{\mathrm{E}}_{\mathrm{tot}}$ was extrapolated for the studied velocities (0.6, 0.8, 1.0, 1.2, and 1.3 $m \cdot s^{-1}$) that are in line with those reported in the literature (up to 1.6 $m \cdot s^{-1}$; Barbosa et al., 2006; Troup, 1991). Velocities until 2.0 $m.s^{-1}$ were included in a complementary analysis representing the of 50, 100 and 200 m breaststroke typical race paces.

Statistics

Data was analysed using SPSS version 25.0 (IBM Corporation, Armonk, NY, USA) and Microsoft Excel for Windows. All the selected variables were checked for normality by the Shapiro-Wilk test and were calculated the mean, standard deviations and 95% confidence intervals. A paired samples t-test compared the time values before and after the intervention program, as well as the bioenergetical variables differences between the two breathing patterns. Cohen's d effect size (d) was computed to assess the magnitude of the effects (interpreted as small - 0.02, moderate - 0.05 and large - 0.08). After did not observing any violations of data homogeneity of variance and normality (p > 0.05) using the Levene's and Shapiro-Wilk tests, ANCOVA analysis examined the differences between breathing patterns concerning the dependent variables while controlling for World Aquatics points and age. The Effect size was computed based on eta-squared (η^2) (interpreted as without effect - $0 < \eta^2 < 0.04$, minimum - $0.04 < \eta^2 < 0.25$, moderate - $0.25 < \eta^2 < 0.64$ and strong -$\eta^2 > 0.64$). Repeated measures ANOVA was used to compare C in the two breathing patterns for the predicted values across different velocities (the statistical significance was set at $\alpha = 0.05$).

3. Results

Table 1 shows the 3 x 25 m all-out test times pre- and post-intervention program, displaying similar values between the two evaluation moments, as well as no differences across the three repetitions in each breathing pattern. Table 2 presents the bioenergetical variables response along the incremental protocol, exhibiting higher values of $\dot{V}O_2$ peak at steps 1 and 2, [La$^-$] at steps 3 and 4, $\dot{E}_{tot}$ and C at step 2, and respiratory frequency and respiratory quotient at steps 2 and 3 when breathing every two cycles comparing to breathing at each cycle. Table 3 demonstrates differences between the two breathing patterns for: (i) velocity from steps 1-4, $\dot{E}_{tot}$ at steps 1, 2 and 5, and respiratory frequency at step 3 when controlling for World Aquatics points and (ii) $\dot{V}O_2$ peak at step 3 and respiratory quotient at step 4 when controlling for age. The World Aquatics points x age interaction showed differences only for $\dot{V}O_2$ peak at step 3.

Table 1 – Mean ± SD (and 95% confidence intervals) pre and post-intervention regarding the 3 x 25 m all-out breaststroke times.

	Pre-intervention			**Post-intervention**		
	Mean	**± SD**	**95% CI**	**Mean**	**± SD**	**95% CI**
1st repetition (s)	18.2	2.8	[16.78; 19.60]	18.2	2.8	[16.78; 19.63]
2nd repetition (s)	18.0	2.6	[16.66; 19.29]	18.0	2.6	[16.71; 19.37]
3rd repetition (s)	18.0	2.7	[16.63; 19.35]	18.0	2.8	[16.58; 19.38]

Table 2 – Mean ± SD and 95% confidence intervals of the bioenergetic related variables when swimming breaststroke breathing every cycle vs two cycles.

		One cycle		**Two cycles**		**Mean diff**	**T-test**	**p**	**95% CI**		**Cohen's d**
		Mean	**±SD**	**Mean**	**±SD**				**lower bound**	**upper bound**	
Velocity ($m.s^{-1}$)	Step 1	0.85	0.12	0.85	0.13	0.00	0.43	0.67	-0.01	0.02	0.11
	Step 2	0.90	0.12	0.89	1.13	0.00	0.64	0.54	-0.01	0.01	0.16
	Step 3	0.93	0.11	0.93	2.13	0.01	1.68	0.12	0.00	0.02	0.45
	Step 4	0.97	0.11	0.97	3.13	0.01	1.35	0.20	0.00	0.02	0.36
	Step 5	1.02	0.10	1.01	4.13	0.02	1.82	0.09	0.00	0.04	0.49
	Rest	7.21	2.03	7.58	2.02	0.38	-0.72	0.48	-1.50	0.74	-0.19
Peak oxygen consumption ($ml·kg^{-1}·min^{-1}$)	Step 1	38.80	8.50	43.31	6.98	4.51	-2.67	**0.02***	-8.14	-0.89	-0.69
	Step 2	45.78	8.79	49.76	7.80	3.99	-2.34	**0.03***	-7.64	-0.33	-0.60
	Step 3	51.25	9.72	52.32	10.95	1.07	-0.45	0.66	-6.18	4.04	-0.12
	Step 4	56.41	8.87	58.62	7.37	2.21	-1.15	0.27	-6.36	1.95	-0.31
	Step 5	62.42	6.00	63.11	7.49	0.68	-0.38	0.71	-4.62	3.25	-0.10
	Rest	2.00	0.91	2.25	0.83	0.25	-1.31	0.21	-0.67	0.16	-0.34

Peak lactate concentration (mmol·l^{-1})	Step 1	3.16	1.75	3.49	1.05	0.33	-0.73	0.48	-1.31	0.65	-0.19
	Step 2	3.39	2.09	3.58	1.18	0.19	-0.54	0.59	-0.92	0.55	-0.14
	Step 3	3.50	2.11	4.33	2.11	0.83	-2.96	**0.01***	-1.44	-0.23	-0.76
	Step 4	4.29	2.65	5.06	2.09	0.77	-2.36	**0.03***	-1.48	-0.06	-0.63
	Step 5	9.13	3.38	7.81	3.13	1.32	2.05	0.06	-0.07	2.71	0.55
Anaerobic alactic contribution (kJ)	Step 1	4.69	0.71	4.69	0.70	0.00	-0.12	0.91	-0.06	0.06	-0.03
	Step 2	4.44	0.68	4.45	0.67	0.01	-0.51	0.62	-0.05	0.03	-0.13
	Step 3	4.17	0.62	4.19	0.63	0.02	-1.35	0.20	-0.06	0.01	-0.36
	Step 4	4.01	0.62	4.03	0.63	0.02	-1.10	0.29	-0.06	0.02	-0.29
	Step 5	3.83	0.62	3.89	0.65	0.06	-1.85	0.09	-0.14	0.01	-0.49
Metabolic power (kJ.min^{-1})	Step 1	37.59	15.21	41.53	13.34	3.94	-2.07	0.06	-8.01	0.13	-0.54
	Step 2	45.14	16.35	49.08	15.25	3.94	-2.34	**0.03***	-7.54	-0.33	-0.60
	Step 3	50.43	18.42	53.02	14.96	2.58	-1.60	0.13	-6.07	0.90	-0.43
	Step 4	56.15	18.25	58.21	15.41	2.06	-1.02	0.33	-6.44	2.32	-0.27
	Step 5	66.53	17.41	65.20	15.71	1.33	0.53	0.61	-4.11	6.77	0.14
Energy cost (kJ.m^{-1})	Step 1	0.72	0.22	0.80	0.18	0.08	-1.97	0.07	-0.18	0.01	-0.51
	Step 2	0.82	0.22	0.90	0.19	0.08	-2.50	**0.03***	-0.14	-0.01	-0.64
	Step 3	0.88	0.24	0.94	0.19	0.06	-1.97	0.07	-0.12	0.01	-0.53
	Step 4	0.95	0.22	1.00	0.20	0.05	-1.46	0.17	-0.11	0.02	-0.39
	Step 5	1.08	0.22	1.08	0.20	0.00	0.04	0.97	-0.08	0.08	0.01
Respiratory frequency (breaths. min^{-1})	Rest	17.54	8.42	15.53	4.68	2.01	1.36	0.20	-1.16	5.17	0.35
	Step 1	33.13	9.70	34.30	30.13	-1.17	-0.53	0.61	-5.94	3.59	-0.14
	Step 2	33.82	9.37	39.77	31.13	-5.94	-2.34	0.03	-11.40	-0.49	-0.60
	Step 3	37.00	7.85	41.03	32.13	-4.02	-3.79	0.00	-6.30	-1.75	-0.98
	Step 4	42.15	10.96	46.03	33.13	-3.88	-1.90	0.08	-8.29	0.52	-0.51
	Step 5	52.36	11.04	53.63	34.13	-1.27	-0.63	0.54	-5.64	3.09	-0.17
Respiratory quotient	Rest	0.90	0.13	0.96	0.16	-0.06	-1.20	0.25	-0.17	0.05	-0.31
	Step 1	0.82	0.11	0.86	35.13	-0.05	-1.94	0.07	-0.10	0.00	-0.50
	Step 2	0.86	0.10	0.95	36.13	-0.09	-4.12	**0.00***	-0.14	-0.04	-1.06
	Step 3	0.93	0.09	1.00	37.13	-0.07	-2.60	**0.02***	-0.12	-0.01	-0.67
	Step 4	0.99	0.15	1.03	38.13	-0.03	-1.10	0.29	-0.10	0.03	-0.29
	Step 5	1.11	0.16	1.13	39.13	-0.03	-1.00	0.33	-0.08	0.03	-0.27

Table 3 – Bioenergetic variables values comparison when breaststroke breathing every cycle vs every two cycles controlling the effect of World Aquatics points and age (* p ≤ 0.05).

		World Aquatics points			Age			World Aquatics points * Age		
		F	P	η^2	F	P	η^2	F	P	η^2
Velocity ($m.s^{-1}$)	Step 1	6.16	**0.02***	0.20	2.30	0.14	0.08	2.79	0.11	0.10
	Step 2	6.30	**0.02***	0.20	2.34	0.14	0.09	2.78	0.11	0.10
	Step 3	4.62	**0.04***	0.16	1.71	0.20	0.07	1.98	0.17	0.08
	Step 4	5.27	**0.03***	0.18	2.55	0.12	0.10	2.77	0.11	0.10
	Step 5	4.19	0.05	0.15	2.61	0.12	0.10	2.74	0.11	0.10
Peak oxygen consumption ($ml·kg−1·min^{−1}$)	Rest	0.25	0.62	0.01	1.81	0.19	0.07	1.33	0.26	0.05
	Step 1	3.36	0.08	0.12	3.11	0.09	0.11	3.18	0.09	0.11
	Step 2	3.43	0.08	0.12	4.06	0.05	0.14	3.76	0.06	0.13
	Step 3	3.53	0.07	0.12	5.72	**0.02***	0.19	4.88	**0.04***	0.16
	Step 4	1.18	0.29	0.05	1.61	0.22	0.06	1.53	0.23	0.06
	Step 5	3.10	0.09	0.11	3.68	0.07	0.13	4.06	0.06	0.14
Peak lactate concentration ($mmol·l^{−1}$)	Rest	0.28	0.60	0.01	1.84	0.19	0.07	1.27	0.27	0.05
	Step 1	0.02	0.89	0.00	0.05	0.82	0.00	0.10	0.75	0.00
	Step 2	0.05	0.83	0.00	0.91	0.35	0.04	0.80	0.38	0.03
	Step 3	0.16	0.70	0.01	0.25	0.62	0.01	0.48	0.50	0.02
	Step 4	0.33	0.57	0.01	0.13	0.72	0.01	0.06	0.82	0.00
	Step 5	0.65	0.43	0.03	2.97	0.10	0.11	1.32	0.26	0.05
Anaerobic alactic contribution (kJ)	Step 1	0.04	0.85	0.00	0.87	0.36	0.03	0.65	0.43	0.03
	Step 2	0.00	0.96	0.00	0.77	0.39	0.03	0.52	0.48	0.02
	Step 3	0.04	0.84	0.00	0.45	0.51	0.02	0.25	0.62	0.01
	Step 4	0.07	0.79	0.00	0.65	0.43	0.03	0.36	0.55	0.02
	Step 5	0.21	0.66	0.01	0.75	0.39	0.03	0.40	0.53	0.02
Metabolic power ($kJ.min^{-1}$)	Step 1	5.19	**0.03***	0.17	1.50	0.23	0.06	2.00	0.17	0.07
	Step 2	4.53	**0.04***	0.15	1.58	0.22	0.06	1.85	0.19	0.07
	Step 3	3.06	0.09	0.11	0.52	0.48	0.02	0.74	0.40	0.03
	Step 4	2.21	0.15	0.08	0.31	0.58	0.01	0.49	0.49	0.02
	Step 5	4.52	**0.04***	0.16	1.76	0.20	0.07	2.13	0.16	0.08
Energy cost ($kJ.m^{-1}$)	Step 1	2.52	0.12	0.09	0.89	0.35	0.03	1.10	0.31	0.04
	Step 2	2.72	0.11	0.10	1.25	0.27	0.05	1.35	0.26	0.05
	Step 3	1.93	0.18	0.07	0.39	0.54	0.02	0.53	0.47	0.02

	Step 4	1.15	0.29	0.05	0.10	0.75	0.00	0.20	0.66	0.01
	Step 5	3.00	0.10	0.11	1.10	0.30	0.04	1.38	0.25	0.05
Respiratory frequency (breaths.min^{-1})	Rest	1.58	0.22	0.06	0.16	0.69	0.01	0.35	0.56	0.01
	Step 1	2.15	0.16	0.08	0.42	0.52	0.02	0.74	0.40	0.03
	Step 2	1.28	0.27	0.05	0.98	0.33	0.04	0.90	0.35	0.04
	Step 3	5.46	**0.03***	0.18	3.33	0.08	0.12	3.83	0.06	0.13
	Step 4	2.98	0.10	0.11	1.27	0.27	0.05	1.64	0.21	0.06
	Step 5	0.51	0.48	0.02	0.05	0.82	0.00	0.00	0.97	0.00
Respiratory quotient	Rest	0.01	0.94	0.00	0.01	0.94	0.00	0.01	0.93	0.00
	Step 1	1.45	0.24	0.06	1.14	0.30	0.04	1.36	0.26	0.05
	Step 2	4.14	0.05	0.14	3.63	0.07	0.13	3.47	0.07	0.12
	Step 3	1.21	0.28	0.05	0.35	0.56	0.01	0.31	0.58	0.01
	Step 4	3.77	0.06	0.14	4.99	**0.04***	0.17	4.09	0.06	0.15
	Step 5	1.79	0.19	0.07	2.79	0.11	0.10	2.21	0.15	0.08

Figure 1 depicts the contributions of the three energy systems for the studied breathing patterns, particularly 0.83 and 1.81% for anaerobic alactic, 9.99 and 7.93% for anaerobic lactic, and 88.18 and 90.26% for the aerobic metabolism for breaststroke breathing-in every cycle vs every two cycles. In addition, it was observed an increase in the anaerobic lactic contribution in the final step of the incremental protocol in both experimental conditions.

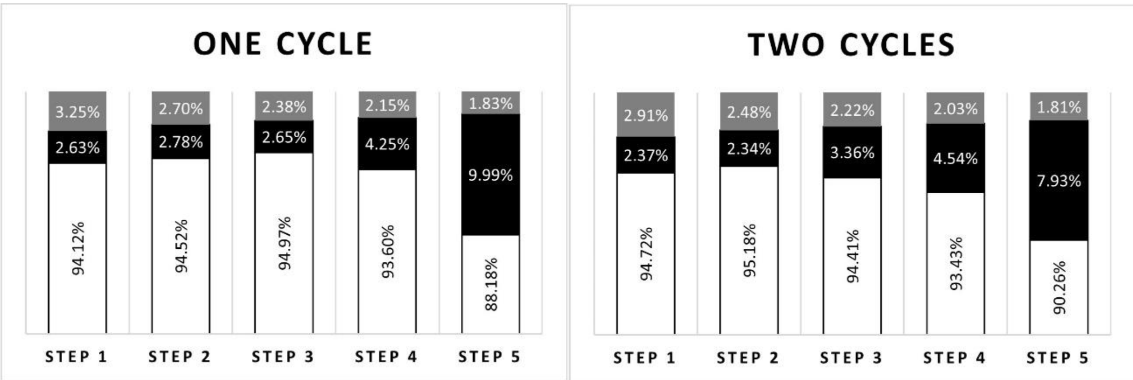


Figure 1 - Percentages of aerobic, anaerobic lactic and anaerobic alactic contributions (white, black and grey, respectively) for breaststroke breathing every cycle and every two cycles.

As described before, linear and exponential regressions were performed to identify the best-fitting model between $\dot{E}_{tot}$ and swimming velocity (Figure 2). Furthermore, an extrapolation for velocities up to 2.0 m.s^{-1} was carried to explore $\dot{E}_{tot}$ values beyond the paces obtained in the experiments. Linear regressions showed strong associations for both breathing patterns and were established as $\mathrm{y} = 132.45\mathrm{x} - 72.683$ for breathing every cycle and $\mathrm{y} = 116.59\mathrm{x} - 54.739$ for breathing at each two cycles (r^2 = 0.74 and 0.72, respectively). Exponential regressions also depicted a very strong association values between variables and were defined as $\mathbf{y} = 3.4043 \times \mathrm{e}^{2.8152\mathrm{x}}$ for breathing every cycle and $\mathrm{y} = 5.7811 \times \mathrm{e}^{2.3412\mathrm{x}}$ for every two cycles (r^2 = 0.75 and 0.72, respectively). However, for breathing-in every cycle vs every two cycles at 2.0 $m.s^{-1}$, the linear regression provided $\dot{\mathrm{E}}_{\mathrm{tot}}$ values of 192.22 and 178.44 $kJ.min^{-1}$, while the exponential approach presented scores of 949.03 and 624.53 $kJ.min^{-1}$ (respectively).

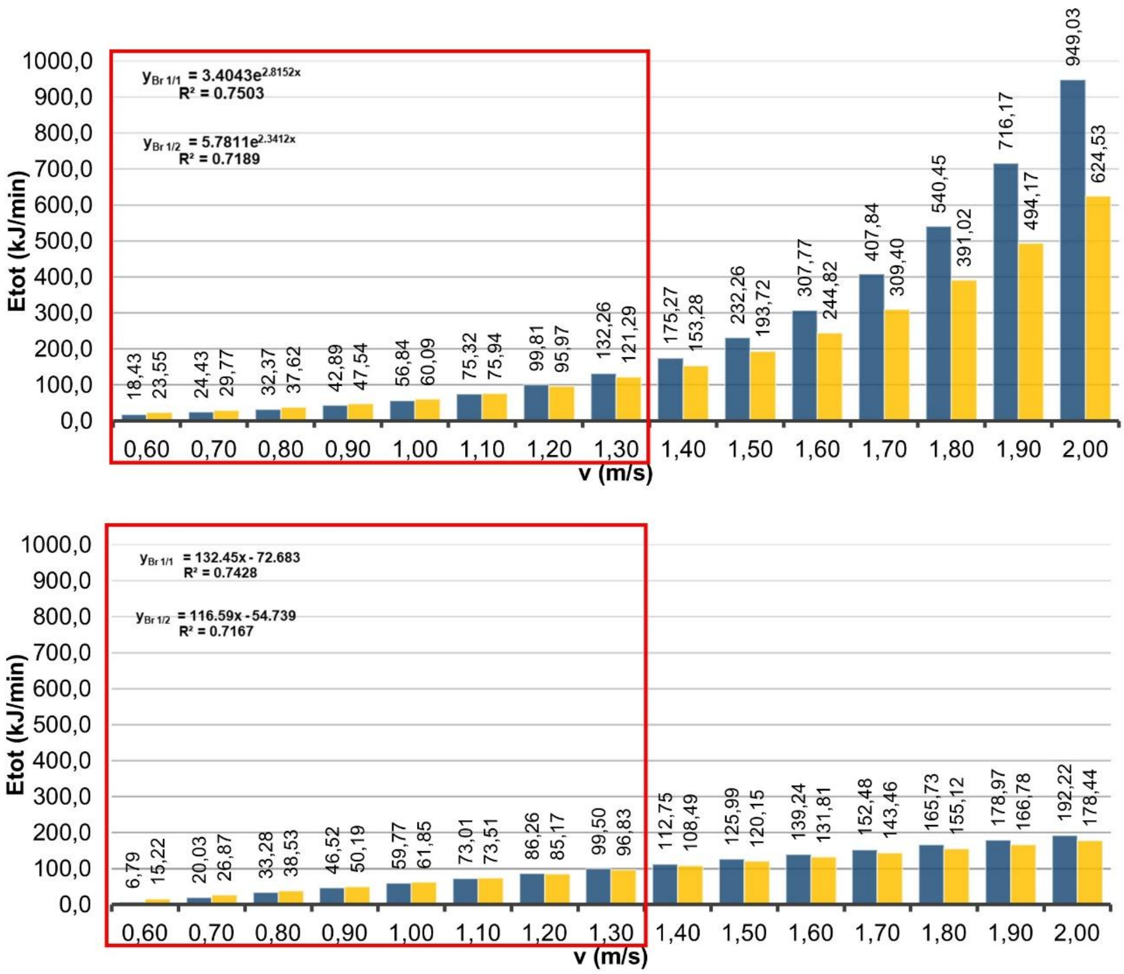


Figure 2 - Relationship between energy expenditure ($\dot{E}_{tot}$) and swimming velocity (v), with the top and the bottom panels depicting the linear and the exponential regression equations used to extrapolate or interpolate $\dot{\mathrm{E}}_{\mathrm{tot}}$ values at velocities ranging from 0.6-2.0 $m.s^{-1}$ for both breathing patterns: in blue for breathing every cycle, and in yellow for breathing every two cycles. The red box highlights velocities studied in the experiments.

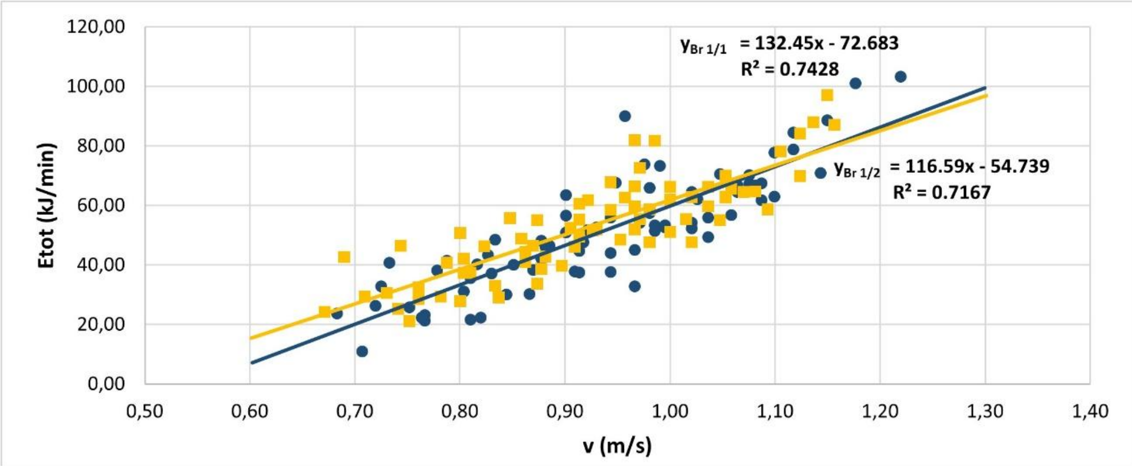


Figure 3 - Relationship between the energy expenditure ($\dot{E}_{tot}$) and the swimming velocity (v). Using the regression equations, values of $\dot{\mathrm{E}}_{\mathrm{tot}}$ were extrapolated or interpolated at velocities of 0.6, 0.8, 1.0, 1.2 and 1.3 m.s^{-1} for both breathing patterns: in blue for breathing every cycle, and in yellow for breathing every two cycles.

The velocities determined in the current study ranged from 0.67-1.22 m.s^{-1} during the incremental protocol when breathing each cycle and every two cycles, with $\dot{\mathrm{E}}_{\mathrm{tot}}$ values being interpolated and extrapolated (using the linear regression equation presented in Figure 2) at velocities ranging from 0.6-1.3 m.s^{-1} for both breathing patterns (Figure 3). Each swimmer linear regression profiles between $\dot{\mathrm{E}}_{\mathrm{tot}}$ and velocity (for both breathing patterns) are presented in Figure 4, with some breaststrokers showing similar regression patterns between the two breathing techniques while others demonstrated distinct regression results for each breathing pattern.

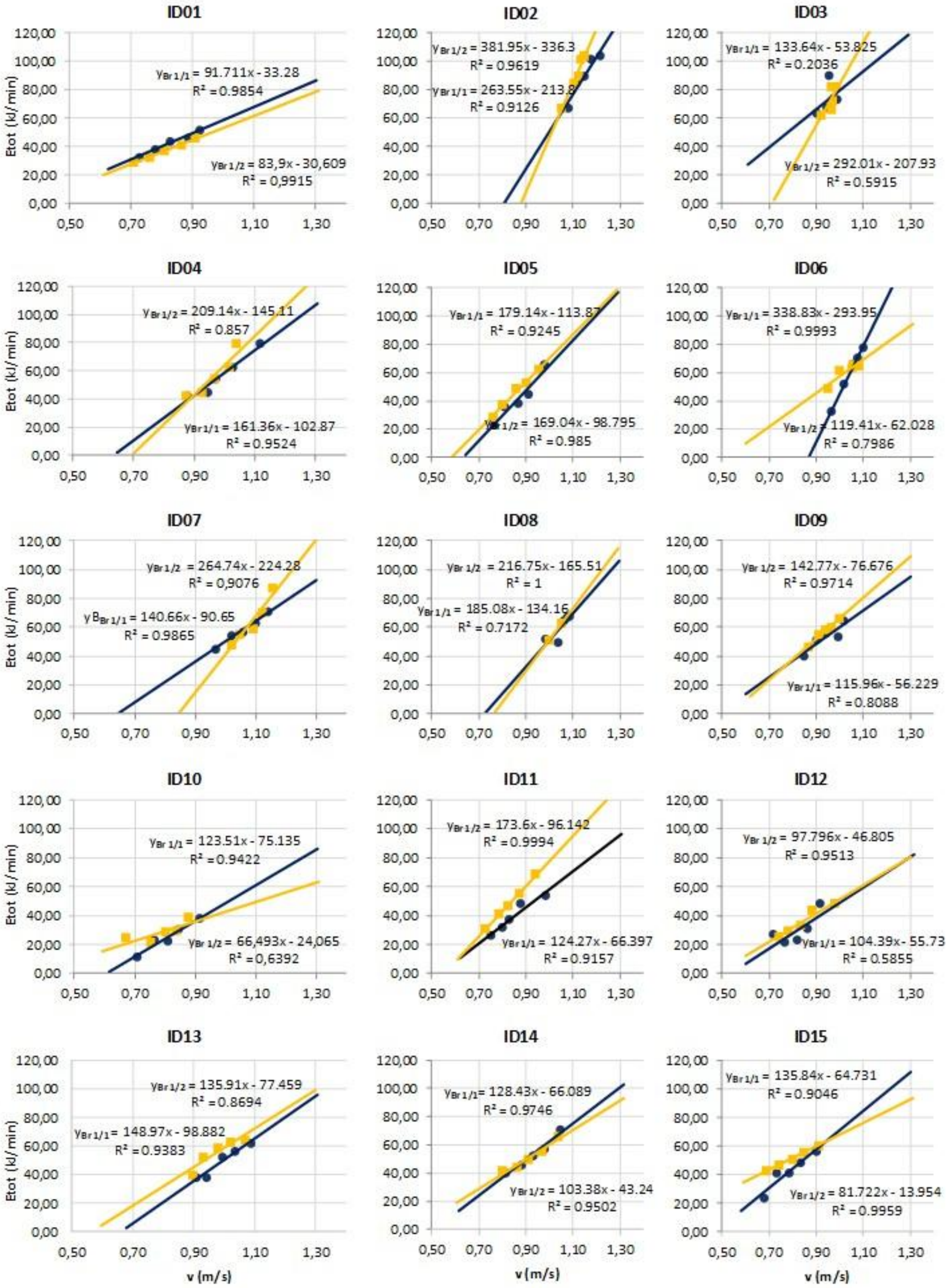


Figure 4 - Individual energy expenditure ($\dot{E}_{tot}$) vs velocity (v) profiles of each swimmer for both breathing patterns: in blue for breathing every cycle, and in yellow for breathing every two cycles. ID08 only managed two steps breathing every two cycles due to fatigue (hence, r^2 = 1).

4. Discussion

The aim of the current study was to compare the C and associated bioenergetic variables in two breaststroke breathing patterns: the common one breath every cycle and a potentially more economical pattern of breathing every two cycles. Age and World Aquatics points were considered as potential confounding variables. We hypothesized that reducing the number of respiratory cycles would decrease C compared to breathing every cycle due to the greater trunk hyperextension associated with the latter pattern. The main findings indicated that, at certain swimming intensities, [La⁻] peak, $\dot{V}O_2$ peak, $\dot{E}_{tot}$ and C were higher with the restricted breathing pattern, i.e., breathing every two cycles. When adjusting for World Aquatics points, breathing every two cycles resulted in higher $\dot{E}_{tot}$ values at steps one, two, and five. This is the first study to examine the C associated with different breathing patterns in breaststroke.

Our findings revealed differences in C and $\dot{E}_{tot}$ between the two breathing patterns only at step 2, where breathing every two cycles resulted in higher values compared to breathing every cycle. Previous research on the influence of different breathing patterns on bioenergetic variables has primarily focused on front crawl and yielded mixed results. Some studies found no differences in [La⁻] between normal vs controlled frequency breathing (Kapus et al., 2003; Key et al., 2014; Murlasits et al., 2023; West et al., 2005), while others reported less [La⁻] during swimming with controlled frequency breathing (Hólmer & Gullstrand, 1980). In addition, controlled frequency breathing has been associated with reduced heart rate and ventilatory responses (West et al., 2005; Key et al., 2014). These findings suggest that the physiological response to controlled breathing patterns may vary depending on the swimming technique, intensity or individual swimmers' characteristics. Despite the differences in findings, the potential benefits of controlled breathing in swimming remain a topic of interest for optimizing performance and training strategies.

It has been suggested that reduced oxygen availability during hypoxia, shifts energy production from aerobic metabolism to glycolysis, increasing [La⁻] production to meet ATP demands (Counsilman, J., 1975). Conversely, elevated carbon dioxide levels have been proposed to inhibit [La⁻] accumulation during exercise, potentially lowering [La⁻] (West et al., 2005; Hólmer & Gullstrand, 1980). These competing mechanisms highlight the complexity of physiological adaptations to breathing patterns and underline the need for further research to clarify the interactions between oxygen availability, carbon dioxide regulation and lactate metabolism in swimming.

We observed that in the protocol steps 3 and 4, peak [La⁻] responses were higher with the restricted breathing pattern (with 0.83 and 0.77 $mmol \cdot l^{-1}$ differences, respectively). Moreover, higher $\dot{V}O_2$ peak values were recorded in the steps 1 and 2 (with 4.51 and 3.99 $ml \cdot kg^{-1} \cdot min^{-1}$ differences, respectively), as well as respiratory quotient scores at steps 2 and 3 (with 0.09 and 0.07 differences, respectively) when breathing every two cycles. These data suggest that performing breaststroke with restricted breathing has distinct bioenergetic impacts compared to front crawl and is in line with prior research that showed that breathing every cycle in 25 m breaststroke results in higher [La⁻] compared to breathing every three cycles (Zompanakis et al., 2021). Previous studies have shown that breaststroke generally exhibits lower [La⁻] and velocity at the anaerobic threshold compared to other swimming techniques (Carvalho et al., 2020; Di Prampero et al., 2008; Holfelder et al., 2013; Marinho et al., 2011), but other ventilatory and metabolic variables, like $\dot{V}O_2$max, appear to be similar between breaststroke and front crawl, suggesting comparable physiological demands (Lomax et al., 2022). These data highlight the slight physiological differences among swimming techniques, emphasizing the need to tailor specific training protocols.

A 12-day intervention program comprising ten 45 min lessons focusing on transitioning swimmers from conventional breaststroke to a wave-action technique was shown to produce substantial changes in swimmers' technique (Sanders, 1995). This relatively short timeframe demonstrates swimmers' capacity to adapt and acquire new skills quickly. Similarly, a study with 16 intervention sessions focused on practicing a specific turning technique in age-group swimmers reported noticeable improvements (Chainok et al., 2023). In our study, the intervention program consisted of 18 sessions conducted over six weeks but the analysis of the 3 x 25 m all-out breaststroke revealed no changes in sprint times pre- vs post-intervention for either breathing pattern. While this suggests consistency in adopting the new breathing pattern, the lack of measurable performance improvements may suggest that the length or intensity of the training program was not enough to elicit substantial gains in performance.

Recruiting high-level competitive swimmers for an intervention aimed at changing a long-trained breathing pattern was challenging. The need for participants to attend sessions twice a week for many hours and engaging in a demanding protocol further limited participation, resulting in considerable variability reflected in the large standard deviations. To address this, an ANCOVA was performed to control for performance and experience effects, using World Aquatics points and age as covariates.

Since swimming pace was imposed for each step of the incremental protocol and for both experimental conditions, no differences in velocity were observed between the two breathing patterns at any stage. However, when controlling for World Aquatics points, velocity differed between the two breathing patterns from steps 1-4, suggesting that the impact of breathing every cycle vs. every two cycles on swimming velocity is influenced by the swimmers' performance level. Breathing every cycle resulted in better performance under these controlled conditions. These scores provide a standardized measure of swimming ability, allowing for an assessment of the impact of breathing patterns independent of individual performance disparities. Swimmers with more World Aquatics points are better able to maintain (or even enhance) velocity when adapting to different breathing patterns, possibly due to greater efficiency or experience in optimizing their technique. In contrast, swimmers with fewer World Aquatics points may experience greater challenge maintaining velocity, as they are less proficient in integrating changes in breathing patterns into their technique. In addition, differences in $\dot{E}_{tot}$ between the two breathing patterns at steps 1, 2 and 5, after controlling for World Aquatics points, suggest that breathing every two cycles led to higher C in some swimming intensities.

The observed differences in anaerobic alactic contribution at step 3, after adjusting for age and the interaction between age and World Aquatics points, suggest that swimmers' age and performance level may modulate the influence of breathing patterns on energy utilization. The interaction between age and World Aquatics points may indicate that more skilled swimmers adapt differently to breathing patterns compared to less experienced counterparts, likely due to differences in training background and energy system efficiency. Furthermore, differences in respiratory frequency were identified at step 3 after adjusting for World Aquatics points, while variations in respiratory quotient were observed at step 4 after controlling for age, highlighting the role of performance level and age-related physiological factors in shaping respiratory adaptations to controlled breathing frequencies.

Across all protocol steps both breathing patterns demonstrated a clear dominance of the aerobic energy pathway, with contributions exceeding 88% in all cases, with minor variations observed at steps 3 and 4. Anaerobic alactic contributions remained nearly identical across both breathing patterns, suggesting that this energy pathway, which primarily relies on phosphocreatine stores for short and high intensity efforts, is not influenced by breathing patterns in breaststroke. The most notable differences were observed in the anaerobic lactic pathway that, while relatively stable, exhibited a slightly higher contribution during step 5 when breathing every cycle compared to every two cycles (9.99 vs 7.93%), suggesting that the less restrictive breathing pattern may increase reliance on lactic acid-producing pathways during the final stages of effort. These findings contrast with the 200 m maximal front crawl, where the energy contributions were 65.9, 13.6 and 20.4% for aerobic, anaerobic lactic, and anaerobic alactic sources (Figueiredo et al., 2011), which might be justified by differences in the specific biomechanics of both swimming techniques and by swimmers' competitive level and age. In addition, the shorter duration of the 200 m front crawl vs 200 m breaststroke could further influence energy contributions, particularly among younger swimmers with slower performances.

Although swimmers employ different coordination patterns across the 50, 100 and 200 m breaststroke competitive events, we extrapolated $\dot{E}_{tot}$ values for velocities ranging from 1.4 to 2.0 $m \cdot s^{-1}$. Previous studies noted that variations in breaststroke velocity are associated with increases in limbs´ velocity, changes in arm-leg coordination and in cycle phase duration (Leblanc et al., 2007; Oxford et al., 2017; Takagi et al., 2004). As velocity increases, greater upper and lower limbs propulsion and shorter glide phases have been reported (Chollet et al., 2004; Seifert & Chollet, 2005; Fernandes et al., 2024), with these coordination changes probably influencing the $\dot{E}_{tot}$ values observed at higher velocities (as described previously for front crawl by Figueiredo et al., 2013b and Zacca et al., 2022).

Although the r^2 values for both exponential and linear regressions were similar across the tested breaststroke breathing patterns, the predicted values from the exponential regression were notably high. The literature reports $\dot{E}_{tot}$ values for breaststroke up to ~2 $kJ \cdot m^{-1}$ (~190 $kJ \cdot min^{-1}$), such as 1.8 $kJ \cdot m^{-1}$ (~162 $kJ \cdot min^{-1}$) at 1.5 $m \cdot s^{-1}$ (Capelli et al., 1998), 1.2 $kJ \cdot m^{-1}$ (~115 $kJ \cdot min^{-1}$) at 1.6 $m \cdot s^{-1}$ (Barbosa et al., 2006) and 2.1 $kJ \cdot m^{-1}$ (~189 $kJ \cdot min^{-1}$) at 1.5 $m \cdot s^{-1}$ (Kolmogorov et al., 2021). In contrast, the exponential regression for breathing every cycle vs. every two cycles estimated $\dot{E}_{tot}$ values of 18.43 vs 23.55 $kJ \cdot min$ at 1.6 $m \cdot s^{-1}$ and 949.03 vs 624.53 $kJ \cdot min$ at 2.0 $m \cdot s^{-1}$. These values, particularly at 2.0 $m \cdot s^{-1}$, significantly exceed those reported in the literature, as there is currently no data supporting $\dot{E}_{tot}$ values in breaststroke at velocities faster than 1.6 $m \cdot s^{-1}$. For comparison, cumulative $\dot{E}_{tot}$ values of 319.3 kJ (~3.8 $kJ \cdot m^{-1}$) were observed for each 50 m segment of a 200 m front crawl race at 1.4 $m \cdot s^{-1}$ (Figueiredo et al., 2011), while C

values of [~0.9-1.6] kJ·m⁻¹ at [~1.35-1.75] m·s⁻¹ for a front crawl incremental protocol (Zacca et al., 2022) and 2.4 kJ·m⁻¹ (~273.6 kJ·min⁻¹) for butterfly swimming at 1.9 m·s⁻¹ (Capelli et al., 1998) were reported.

Therefore, the linear regression appears to be the best-fit model, consistently with previous findings reporting that breaststroke C and $\dot{E}_{tot}$ increase linearly across a range of velocities (Capelli et al., 1998; Vilas-Boas & Santos, 1994). While theoretical models propose that energy output should scale with the cube of velocity, the observed linear relationship can be attributed to variations in coordination and overall efficiency across different velocities (Vilas-Boas & Santos, 1994). This discrepancy might result from a relatively more pronounced efficiency increase compared to drag as swimming velocity rises (Vilas-Boas & Santos, 1994). In addition, the substantial energy expenditure required to accelerate the body during the push phase likely contributes to this pattern, compensating for the velocity loss during the non-propulsive phase of the cycle (Capelli et al., 1998; Fernandes et al., 2024).

We conducted an individual analysis of each swimmer because the sample variability may have contributed to the lack of statistical differences in the group analysis. Moreover, individual swimmers exhibit unique characteristics, leading to highly individualized responses (Fernandes et al., 2005; Dadashi et al., 2013; Fernandes et al., 2024). For some swimmers (e.g., ID04 and ID11), restricted breathing led to a steeper slope, indicating $\dot{E}_{tot}$ increased more rapidly with velocity. Conversely, for others (e.g., ID01 and ID10), breathing every cycle had the steeper slope, suggesting higher energy demands at faster velocities. In most cases, breathing every two cycles had a higher intercept at baseline, indicating greater energy demands at slower velocities, possibly due to mechanical inefficiency or disrupted pacing. The r^2 values were generally high, particularly for breathing every two cycles (e.g., ID02 and ID05), indicating that the linear model explained most of the variance in $\dot{E}_{tot}$. However, for some swimmers (e.g., ID03), r^2 was low, suggesting greater variability or inconsistency in $\dot{E}_{tot}$, possibly due to experimental noise, individual physiology, or poor adaptation to the breathing pattern.

Some swimmers (e.g., ID01 and ID12) showed minimal differences in $\dot{E}_{tot}$ between breathing patterns, suggesting adaptability to either pattern, while others (e.g., ID02 and ID07) showed substantial differences, indicating a preference for one pattern over the other. Data suggests that breathing every cycle may be more efficient for some swimmers, particularly at higher velocities, as shown by shallower slopes and higher r^2 values. For these swimmers (e.g., ID07 and ID11), breathing every two cycles may disrupt rhythm and increase $\dot{E}_{tot}$. The choice of breathing pattern appears to involve a trade-off: breathing every cycle provides more oxygen but may increase drag, while breathing every two cycles improves streamline efficiency but limits oxygen availability, especially at higher intensities.

5. Limitations and future research

The current study is the first to investigate the C associated with different breathing patterns in breaststroke technique but presents certain limitations. Firstly, it examines only two breathing patterns, without addressing the potential effects of additional breath-holding strategies. Secondly, the incremental protocol based on 200 m distances may limit the regression analysis at faster velocities, which are more typical of 50 and 100 m events. This limitation may reduce the application of these findings to such shorter and more intense events. Finally, although an ANCOVA was conducted to account for performance level variability within the sample, a more homogeneous group would likely yield more robust comparative results. Future research could build on these findings by exploring whether modifications in the intervention period (e.g., training duration) and cohort characteristics (e.g., performance level or age group) might enhance the adoption and benefits of the new breathing pattern.

6. Conclusions

Our study compared the C and associated bioenergetic variables between two breathing patterns (breathing every cycle and every two cycles) in the breaststroke technique, while accounting for age and World Aquatics points as potential confounding variables. The results showed that, in certain test steps, $[La^-]$ peak (step three and four), $\dot{V}O_2$ peak (step one and two), $\dot{E}_{tot}$ (step two) and C (step two) were higher when breathing every two cycles. When adjusting for World Aquatics points, breathing every two cycles resulted in higher $\dot{E}_{tot}$ values at steps one, two, and five. These findings indicate that breathing every two cycles leads to higher bioenergetic demands across the tested intensities (steps 1 to 5), especially at moderate to high effort levels. Nonetheless, this pattern may still offer advantages in sprint events (e.g., 50 m and 100 m), where performance relies more on anaerobic metabolism and neuromuscular power. This highlights a relevant practical consideration for coaches and swimmers when tailoring breathing strategies to race distance and individual characteristics.

Chapter 4. Exploring the impact of breathing patterns on active drag in breaststroke swimming

Miriam Alves*[1,2,3], Tiago M. Barbosa[4,5], João Paulo Vilas-Boas[1,2,3]

[1] Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D);

[2] Porto Biomechanics Laboratory (LABIOMEP-UP);

[3] Faculty of Sport, University of Porto, 4099-002 Porto, Portugal;

[4] Department of Sport Sciences, Instituto Politécnico de Bragança, 5300-252 Bragança, Portugal;

[5] Research Centre for Active Living and Wellbeing (LiveWell), Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal

Alves, M., Barbosa, T. M., & Vilas-Boas, J. P. (2024). Exploring the impact of breathing patterns on active drag in breaststroke swimming. *Journal of biomechanics*, 112390. https://doi.org/10.1016/j.jbiomech.2024.112390

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 cycle versus every two cycles. 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 cycles, with some achieving higher velocities. Conversely, nine swimmers exhibited lower D_a values while breathing every cycle, with six of them also showing higher velocity values compared to breathing every two cycles. 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.

KEY-WORDS: HYDRODYNAMICS; SWIMMING; PERFORMANCE; BIOMECHANICS

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, 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 technique (Sacilotto et al., 2023).

Among the various swimming techniques, studies have noted that breaststroke tends to have higher values of frontal area and D_a (Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997, 2021). In this technique, swimmers take a breath during each 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 cycle to breathe; 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: breathing every cycle and every two cycles. It was hypothesized that breathing every two cycles would result in lower active drag compared to breathing every cycle.

2. Methods

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 100m breaststroke. The swimmers participated in regular training sessions between 6 to 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 (100m 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

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).

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):

$$D_a = \frac{D_b \times v_b \times v^2}{v^3 - {v_b}^3} \quad (2)$$

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):

$$P_{tot} = D_a \times v \quad (3)$$

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:

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

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}).

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 85N (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.

Table 2 – Swimmers' basic hydrodynamic characteristics swimming breaststroke breathing every cycle (Br 1/1) and every two 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; C_{Da} (ad) – dimensionless coefficient of hydrodynamic force; Pto(W) - total external mechanical power.

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 ≤ η^2 ≤ 0.003).

Table 3 – Comparison of the hydrodynamics swimming breaststroke breathing every cycle (Br 1/1) and every two cycles (Br 1/2).

	Br 1/1 Mean ± SD [95 CI]	**Br 1/2** Mean ± SD [95 CI]	**T-test**	**p**	**CI**	**Cohen's d**
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
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; C_{Da}(ad) – dimensionless coefficient of hydrodynamic force; Pto(W) - total external mechanical power.

Table 4 – ANCOVA test, of the hydrodynamics swimming breaststroke breathing every cycle (1/1) and every two cycles (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
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; C_{Da}(ad) - dimensionless coefficient of hydrodynamic force; Ptot(W) - total external mechanical power.

4. Discussion

This study aimed to compare D_a, C_{Da} and, P_{tot} between two breathing patterns in the breaststroke technique: inhaling every cycle versus every two cycles. It was hypothesized that breathing every two cycles would result in lower D_a compared to breathing every cycle. 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 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 Kolgomorov´s 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 cycle 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 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 cycle 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 cycles, indicating potential efficiency gains for this subgroup. Conversely, 60% of the swimmers exhibited higher D_a values with the every two cycles breathing pattern compared to breathing every cycle. 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.

Chapter 5. Analyzing breathing patterns in the breaststroke technique through dual media kinematics and fractal dimension

Miriam Alves[1,2,3], Pedro Fonseca[2,3], Aléxia Fernandes[1,2,3], André V. Brito[1,2,3], Tiago M. Barbosa[4,5], João Paulo Vilas-Boas*[1,2,3]

[1] Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D);

[2] Porto Biomechanics Laboratory (LABIOMEP-UP);

[3] Faculty of Sport, University of Porto, 4099-002 Porto, Portugal;

[4] Department of Sport Sciences, Instituto Politécnico de Bragança, 5300-252 Bragança, Portugal;

[5] Research Centre for Active Living and Wellbeing (LiveWell), Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal

Alves, M., Fonseca, P., Fernandes, A., Brito, A. V., Barbosa, T. M., & Vilas-Boas, J. P. (2025). Analyzing Breathing Patterns in the Breaststroke Technique Through Dual-Media Kinematics and Fractal Dimension. *Sensors*, 25(10), 3104. https://doi.org/10.3390/s25103104.

Abstract

The most hydrodynamic position in swimming is, in general, achieved when the head is submerged, emphasizing the importance of minimizing breathing frequency to preserve efficiency. This study aimed to characterize and compare kinematics between two breaststroke breathing patterns, breathing every cycle and breathing every two cycles, while also analyzing intra-cyclic velocity variation (dv) and fractal dimension. This resulted in three types of cycles: (i) the breathing cycle, (ii) the non-breathing cycle, and (iii) the breathing cycle following a non-breathing cycle. To ensure familiarity with the new breathing pattern, swimmers underwent a six-week intervention program before testing. They then performed three maximal 25 m bouts in each breathing pattern. Kinematic data were collected using a dual-media optoelectronic system (Qualisys AB, Sweden), integrating underwater and dry-land camera recordings. The results showed that differences between the three breaststroke swimming cycles were minimal. The non-breathing cycle had the shallowest and deepest head positions, the lowest horizontal head amplitude out of water, and the smallest vertical head amplitude. It also had the fastest maximum vertical velocity of the feet and maximum center of mass velocity in the swimming direction.

KEY-WORDS: SWIMMING; BREATHING PATTERNS; KINEMATICS; CENTER OF MASS

1. Introduction

Achieving high swimming velocity requires optimizing propulsion while minimizing resistance (Toussaint & Beek, 1992). The most hydrodynamic position in swimming is achieved, in general, when the head is submerged, highlighting the importance of minimizing breathing frequency during a race to preserve efficiency (Pendergast et al., 2005). Studies have shown that expert swimmers take fewer breaths to maintain an optimal streamlined body position and sustain efficient propulsion (Cardelli, 2000). However, excessively minimizing breathing frequency may compromise propulsion, as breathing also supports rhythm and oxygen supply (Pendergast et al., 2005). This balance is particularly influenced by race distance, with shorter events often allowing reduced breathing frequency, while longer races may require more frequent breathing to meet physiological demands (Pedersen & Kjendlie, 2006). Nevertheless, there is limited research on the impact of breathing on kinematics across various swimming techniques.

In butterfly technique, breathing has been shown to cause a decrease in velocity, increased body inclination during inhalation, and prolonged upper limbs recovery times (Alves et al., 1999; Hahn and Krug, 2013; Fernandes et al., 2024). Additionally, reduced propulsive continuity between upper and lower limb actions has been observed while breathing, resulting in a shorter downward leg kick (propulsive phase), extended less-propulsive phases (such as the upper limb catch and upward leg kick) and increased glide time (Seifert et al., 2010). In front crawl, breath-holding has been associated with faster 25 m time-trials compared to higher breathing frequencies (Couto et al., 2014; Pedersen & Kjendlie, 2006) and is a standard procedure by expert sprinters racing short distances. Breathing has been found to increase cycle duration and influence hand displacement patterns, resulting in shallower hand paths, slower vertical hand acceleration during the pull phase, and a slowdown in the horizontal velocity of the center of mass (McCabe et al., 2015; Vezos et al., 2007). In breaststroke, where research is more limited, breathing every three cycles enabled swimmers to cover a 25 m distance in less time than breathing every cycle (Zompanakis et al., 2021). However, when comparing active drag and velocity between two breathing patterns, similar values were attained in 13 m breast-stroke bouts (Alves et al., 2024).

Given that breathing changes body position and affects propulsion, it is paramount to understand how these changes influence intra-cyclic velocity variation (dv), a key parameter in swimming performance (Fernandes et al., 2023). Over the course of a swimming cycle, the intensity of hydrodynamic drag and propulsion vary constantly, since the motor actions of the upper and lower limbs and trunk are fairly discontinuous (especially in breaststroke and butterfly techniques). Thus, in each cycle, the velocity changes as a result of the positive and negative accelerations induced by the continuous variations of the resulting mechanical impulse (Barbosa et al. 2010). Breaststroke has been defined as the swimming technique with the greatest dv, characterized by a two-peak profile (Barbosa et al., 2013). A correlation between the dv and energy cost was reported (Barbosa et al., 2010; Vilas-Boas, 1996), signaling that swimmers who exhibit fewer fluctuations are more likely to swim economically. Since breathing disrupts the swimmer's streamlined position and causes fluctuations in propulsion, it is likely to influence dv. Understanding this relationship is essential, as dv reflects the extent of velocity fluctuations within a swimming cycle.

In the analysis of dv, discrete values are commonly used for quantification. Coefficient of variation computation is the mainstream procedure to quantify dv (Barbosa et al., 2006; Figueiredo et al., 2012; Matsuda et al., 2014; Miller, 1975), but literature presents conflicting results, showing higher and/or lower dv in elite swimmers. For instance: swimmers achieve higher mean velocities when presenting lower intra-cycle velocity variation in the four swimming techniques (Barbosa et al., 2013); higher mean velocities maintaining their intra-cycle velocity variation values in the front crawl (de Jesus et al., 2016); and no relationship between intra-cycle velocity variation and front crawl performance (Psycharakis et al., 2010). Some authors put forward that higher-level swimmers present lower intra-cycle velocity variation than lower-level or less experienced swimmers due to their improved technique, suggesting its inverse relationship with competitive level (Matsuda et al., 2014; Schnitzler et al., 2008). Conversely, others argued that elite swimmers display higher intra-cycle velocity variation due to higher cycle peak velocities and corresponding larger resistive forces (Psycharakis et al., 2010). Considering that swimming cycles have a time dimension, a continuous assessment of differences throughout the cycle would provide a complementary approach (Fernandes et al., 2024; Morais et al., 2023; Vieira et al., 2024). Therefore, using the Statistical Parametric Mapping could not only supplement the discrete dv data, but also offer a more detailed perspective on velocity variation over time.

Taking into consideration the state of-the-art on dv, recent studies have incorporated non-linear analyses like fractal dimension (FD) to assess the complexity of motion in cyclic sports. Expanding on this approach, motor control methods have been applied to swimming to evaluate motion variation through stability and complexity calculations, providing additional insights into time series variability (Barbosa et al., 2017a). FD is an invariant non-linear parameter that characterizes systems exhibiting fractality or other properties that remain consistent over time and/or space (Bravi et al., 2011). As rule of thumb, as FD increases, so does the complexity of the time series. Fractal dynamics in competitive sports has been reported in running, rowing, cycling and swimming (Barbosa et al., 2017a; Den Hartigh et al., 2015; Hoos et al., 2014; Slopecki et al., 2024; Tucker et al., 2006). However, no study has examined whether changes in FD are sensitive to modifications in technical patterns, such as different breathing patterns in swimming.

Given the limited research on breaststroke breathing patterns and the impact of breathing on kinematics and nonlinear parameters, such as FD, in other swimming techniques, this study aimed to characterize and compare two breaststroke breathing patterns: breathing every cycle and breathing every two cycles. Additionally, we aimed to analyze and compare dv and FD between these two breathing patterns. In the breathing every cycle pattern, each cycle included a breath. In the breathing every two cycles pattern, each pair of cycles includes one non-breathing cycle followed by a breathing cycle, which we specifically refer to as the breathing cycle following a non-breathing cycle to avoid any confusion with the consecutive breathing cycles. This distinction leads to the study of three types of cycles: (i) the breathing cycle, (ii) the non-breathing cycle, and (iii) the breathing cycle following a non-breathing cycle. We hypothesized that the non-breathing cycle would be associated with changes in kinematics compared to the breathing cycle. Furthermore, we hypothesized that a reduced breathing pattern would lead to lower dv and reduced FD.

2. Methods

Participants

Fifteen swimmers (nine females and six males) from local swimming teams participated in the study. Their competitive level was determined based on their personal best performance in the 100 m breaststroke in a 25 m pool, assessed using FINA points as defined by World Aquatics. The primary physical and performance characteristics of the participants were as follows: 16.7 ± 5.5 and 15.9 ± 3.0 years old, 49.4 ± 10.1 and 57.0 ± 11.6 kg of body mass, 158.9 ± 9.2 and 169.3 ± 10.1 cm of height and 355.7 ± 97.8 and 376.2 ± 122.6 FINA points for females and males, respectively. Swimmers were recruited based on the following criteria: (i) a minimum of five years of competitive swimming experience, (ii) participation at least at the regional competitive level, and (iii) absence of injuries in the six months prior to the evaluations. The study was approved by the local ethics committee (CEFADE 36/2022) and adhered to the principles outlined in the Declaration of Helsinki (2000). Participants (or their legal guardians, in the case of minors) were fully informed about the procedures, potential risks, and benefits of the study and provided written consent to participate.

Intervention Program

To familiarize swimmers with the pattern of breathing every two cycles, a six-week intervention program was implemented prior to the evaluation. The program consisted of 18 sessions (three per week, 20 minutes each) conducted in a 25 m indoor pool. Designed to progressively increase difficulty, the program introduced challenges beyond the swimmers' existing skill levels to facilitate skill acquisition (Guadagnoli & Lee, 2004). The intervention began after the main competition of the season's first macrocycle, coinciding with the transition to the second macrocycle. In the first session, swimmers watched a video demonstrating the new breathing pattern and were given the opportunity to self-explore it in the water. When introducing the new breathing pattern, swimmers were informed that the goal was to explore a new breathing pattern and to develop the technical ability to execute it consistently and effectively. The focus was on skill acquisition and familiarization rather than on performance enhancement per se. Swimmers were not told that this strategy was expected to improve or impair performance, in order to minimize potential expectancy effects. The aim was to ensure that participants approached the intervention with an open and exploratory mindset. During the first week, the coach provided feedback that gradually transitioned from analytical to holistic technical training. Over the next two weeks, swimmers completed three low-intensity sessions with increasing volume. In weeks four and five, the program emphasized increased intensity. The final week alternated between volume and intensity. Throughout the sessions, swimmers received targeted coaching feedback on technical aspects to enhance their performance.

Motion Capture System

Kinematics were collected using a dual-media optoelectronic system (Qualisys AB, Sweden), which merged the information recorded by an underwater and dry-land camera system. The underwater system included 7 cameras (6 x Oqus 300+u, 1 x Oqus 700+u), while the dry-land system included 9 cameras (6 x Oqus 400, 3 x Oqus 310+). Both systems were synchronized and recording at a 100 Hz sampling frequency.

The two systems were independently calibrated, starting with the positioning of a static L-frame to set the origin of their global coordinate system (GCS). Then, a dynamic calibration was performed with a fixed-length wand to obtain a calibrated volume of approximately 5.5 x 2.0 x 1.5 meters in the middle of the pool. Next, a twin-calibration was performed to align and superimpose the dry-land system GCS to that of the underwater system, which became the twin GCS. With this, a three-dimensional dual-media working volume was enabled, where the orthogonal axes were defined as Y for horizontal (swimming direction), X for the mediolateral and Z for vertical displacements, respectively. These procedures were performed in accordance with the manufacturer instructions (Qualisys Track Manager User Manual), resulting in a twin-system error of less than 1.5 mm. To assess the water level relative to the twin system GCS origin, a short data acquisition was carried out. For that purpose, the calibration wand was placed parallel to the water surface, at its height. Thereafter, all values in the Z-axis were considered negative if performed below this level.

In order to model the swimmer throughout the tests, a set of 50 retroreflective markers were placed on pre-selected anatomical landmarks. These were based on a modified version of the Qualisys Sports Marker Set (2021), with the addition of markers: #3 on the head, #24 on the hands and #16 and #20 on the feet (Figure 1, Appendix 1). Each spherical marker had 19 mm of diameter, and was attached to a 20 mm flat base. This base was first attached to the skin with double-sided tape, and then covered with a transparent waterproof tape (Euroderm, Eurofarm, Italy). To avoid peeling due to water infiltration, the edges of this tape were reinforced with kinesiology tape (Leukotape, BSN medical), similarly to the waterproofing procedure reported in electromyography

(Andersen et al., 2023). Once this process was finished, the marker was attached to the base.

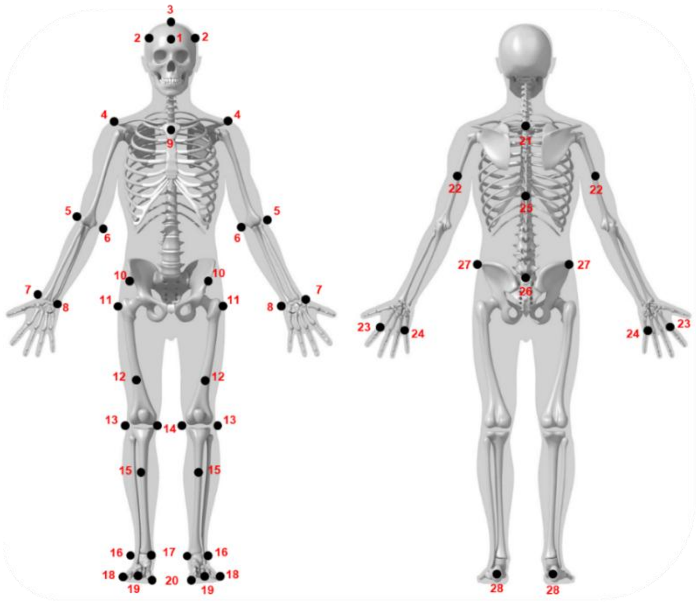


Figure 1. Schematic representation of the full-body swimming marker set.

Data Collection Procedures

The evaluation sessions were conducted in a 25 m indoor pool with a depth of 1.80 m. Swimmers completed a typical 1,000 m individual race preparation warm-up. Afterwards, they performed three maximal bouts of 25 m in each breathing pattern, breathing every cycle and breathing every two cycles, with the order of the breathing conditions randomized to minimize order effects. No differences were found between the time trials, indicating that there was no observable order effect on performance. Between trials, swimmers passively rested for four minutes, a period considered sufficient to avoid acute and cumulative effects of fatigue (Toubekis et al., 2011). After each trial, all swimmers were informed of their trial time, which was expected to be within ± 2.5% of the targeted race pace. If this was not achieved, the subject was invited to repeat the trial. This approach was chosen to minimize the number of repeated trials due to incorrect pacing or deviation from the intended maximal effort, which could also compromise data quality and introduce fatigue. Out of the 90 bouts performed, 11 did not meet the predefined criteria and were repeated.

Data Analysis and Processing

The markers trajectories were identified in Qualisys Track Manager (Qualisys AB, Sweden), and trajectory gaps were filled with polynomial and relational interpolations. Then, the resulting trajectories were exported to Visual 3D v 5.01.21 (HAS-Motion, Canada), where they were low-pass filtered with a 6 Hz Butterworth low-pass filter (Roithner et al., 2000), and a 6 degrees-of-freedom biomechanical model was created. The same filter was applied to the calculated joint angles.

A full cycle was set as the period from the beginning of the upper limbs' outsweep until the same discrete event happened again. Two consecutive swimming cycles, taken in the middle of the calibrated volume, were analyzed. A total of 173 cycles were studied. Three types of cycles were defined: (i) the breathing cycle, (ii) the non-breathing cycle, and (iii) the breathing cycle following a non-breathing cycle. This means that, in the breathing every cycle condition, all cycles were breathing cycles. In contrast, in the breathing every two cycles condition, each pair of cycles consisted of one non-breathing cycle followed by a breathing cycle, which we specifically refer to as the "breathing cycle following a non-breathing cycle." This distinction allowed us to analyze how the presence or absence of a preceding breath or non-breathing cycle influenced kinematics.

The analyzed variables were categorized as: (i) movement amplitude, (ii) joint angles, and (iii) swimming velocity. The movement amplitude described the motor path of the center of mass of the hands, feet, head, and the body's CoM during a complete swimming cycle. The centers of mass of each body segment and the full body were automatically calculated by the software (Visual3D), according to anthropometrical biomechanical tabled values (Hanavan anthropometrical model). Vertical movements included minimum and maximum depth, as well as its amplitude (the difference between these values). Horizontal amplitude measured the displacement between the most forward and rearward points, while medial-lateral amplitude accounted for the lateral variation of position. Two indices complemented these measurements (Vilas-Boas, 1993): the horizontality index (ratio between medio-lateral and vertical amplitudes during the propulsive phases) and the anterior-posterior stabilization index in the sagittal plane (ratio between vertical and horizontal amplitudes during the propulsive phases). Joint angles assessed the hip, knee, and trunk sagittal amplitude. Finally, velocities were analyzed for the CoM, feet, hands, and head, considering minimum, mean, and maximum values in each direction (X, Y, and Z-axis). For variables of the feet and hands, the average between left and right side were considered. All these variables are further described in detail in Appendix 2.

The intra-cycle mean variation and the fractal dimension were derived from the CoM velocity in the swimming direction. Intra-cycle mean velocity variation was obtained by the calculation of the coefficient of variation as suggested by Miller (1975) and reported in literature (Barbosa et al., 2006; Figueiredo et al., 2012; Matsuda et al., 2014). Fractal dimension (FD) was determined using Higuchi's method (Higuchi, 1988), which has also been applied in swimming research (Barbosa et al., 2016, 2017a):

$$FD = \frac{d \log N (L (k))}{d \log (k)} \tag{1}$$

where FD is the fractal dimension, N is the number of new points from the speed-time series and k is the scaling factor.

Statistical Analysis

Mean, standard deviation, and 95% confidence intervals were calculated for all variables. Data normality was assessed using the Shapiro–Wilk test. A repeated measures ANOVA (within-subjects) was conducted to compare the three cycle types: breathing cycle, non-breathing cycle, and breathing cycle following a non-breathing cycle, with statistical significance set at $p < 0.05$. Then, post-hoc tests with Bonferroni correction were performed. Effect sizes were evaluated using partial eta squared (ηp^2) and interpreted as: no effect ($0 < \eta^2 \leq 0.04$), small ($0.04 < \eta^2 \leq 0.25$), moderate ($0.25 < \eta^2 \leq 0.64$), and strong ($\eta^2 > 0.64$) (Ferguson, 2009). To further analyze velocity fluctuations throughout the stroke cycle, breaststroke cycles were time-normalized to 101 data points, and Statistical Parametric Mapping (SPM) ANOVA tests were applied using MATLAB R2023b (The MathWorks Inc., Natick, Massachusetts, United States).

3. Results

Data revealed that the minimum and maximum head depths varied across the three cycles. In Table 1, both the breathing cycle and the breathing cycle following a non-breathing cycle showed deeper minimum depths ($p < 0.001$; $F = 25.096$; $\eta^2 = 0.596$) and shallower maximum depths ($p < 0.001$; $F = 7.925$; $\eta^2 = 0.318$) compared to the non-breathing cycle. Additionally, the head's vertical amplitude was lower in the non-breathing cycle ($p = 0.03$; $F = 8.919$; $\eta^2 = 0.344$). The horizontal amplitude of the head's motor path out of the water differed between the cycles ($p < 0.001$; $F = 32.378$; $\eta 2 = 0.656$), with the breathing cycle exhibiting the highest values, followed by the breathing cycle after a non-breathing cycle, and then the non-breathing cycle. In Table 3, the minimum medio-lateral velocity (X-axis) of the CoM also differed ($p = 0.04$; $F = 6.094$; $\eta 2 = 0.264$), with the breathing cycle showing the lowest value. Furthermore, the maximum vertical velocity (Z-axis) of the feet was higher in the non-breathing cycle compared to the other two cycles ($p = 0.018$; $F = 4.482$; $\eta 2 = 0.209$). The maximum velocity in the swimming direction of the CoM (Y-axis) was greater in the non-breathing cycle compared to other two cycles ($p = 0.02$; $F = 7.180$; $\eta 2 = 0.297$).

The breathing cycle and the non-breathing one differed in the medio-lateral mean velocity of the head ($p = 0.029$; $F = 3.726$; $\eta 2 = 0.180$). The breathing cycle and the breathing cycle following a non-breathing cycle differed in the medio-lateral amplitude of the hands ($p = 0.08$; $F = 5.667$; $\eta 2 = 0.250$) and in the minimum vertical velocity of the CoM ($p = 0.005$; $F = 5.931$; $\eta 2 = 0.259$). The breathing cycle presented higher values in the two variables.

Between the non-breathing cycle and the breathing cycle following a non-breathing cycle, several kinematic differences were observed. The mean vertical velocity of the feet was also higher in the non-breathing cycle than in the breathing cycle following a non-breathing cycle ($p = 0.010$; $F = 5.496$; $\eta 2 = 0.244$). In contrast, the maximum vertical velocity of the head was greater in the breathing cycle following a non-breathing cycle than in the non-breathing cycle ($p = 0.035$; $F = 3.830$; $\eta 2 = 0.184$). Similarly, the mean velocity of the head in the swimming direction was higher in the non-breathing cycle than in the breathing cycle following a non-breathing cycle ($p = 0.019$; $F = 4.101$; $\eta 2 = 0.194$). Lastly, the minimum vertical velocity of the head was different between the non-breathing cycle and the breathing cycle following a non-breathing cycle ($p = 0.039$; $F = 3.507$; $\eta 2 = 0.171$).

No differences were found between the three cycles in the joint angles (Table 2), in the coefficient of variation of the dv and, in the FD (Table 4). In the SPM analysis (Figures 2, 3 and 4), the mean velocity curve was similar between the three cycles demonstrating a comparable variation, highlighting that the cycles are performed similarly.

Table 1. Movement amplitudes of the hand, foot, head, and CoM, along with repeated measures ANOVA results.

	Variables	Breathing cycle Mean ± SD [95%CI]	Non-breathing cycle Mean ± SD [95%CI]	Breathing cycle following a non-breathing cycle Mean ± SD [95%CI]	F	η²
Hands motor path	Min depth (m)	-0.02 ± 0.05 [-0.03; -0.01]	-0.03 ± 0.05 [-0.04; -0.01]	-0.03 ± 0.09 [-0.06; 0]	0.435	0.025
	Max depth (m)	-0.34 ± 0.05 [-0.35; -0.33]	-0.35 ± 0.05 [-0.37; -0.34]	-0.32 ± 0.08 [-0.35; -0.30]	2.124	0.111
	Vertical amplitude (m)	0.32 ± 0.08 [0.31; 0.34]	0.33 ± 0.08 [0.30; 0.35]	0.29 ± 0.15 [0.25; 0.34]	1.577	0.085
	Horizontal amplitude (m)	1.11 ± 0.23 [1.06; 1.16]	1.13 ± 0.24 [1.06; 1.20]	1.11 ± 0.21 [1.04; 1.17]	0.319	0.018
	Medio-lateral amplitude (m)	**0.40 ± 0.06**[c] [0.39; 0.41]	0.40 ± 0.06 [0.38; 0.42]	**0.38 ± 0.06**[a] [0.37; 0.40]	5.667	0.250
	Horizontality index	0.30 ± 1.47 [-0.59; 0.00]	0.29 ± 1.40 [-0.70; 0.11]	0.30 ± 1.39 [-0.75; 0.16]	0.0078	0.205
	Antero-posterior stabilization index in the sagittal plane	1.00 ± 0.80 [0.84; 1.16]	0.75 ± 0.69 [0.55; 0.95]	0.91 ± 1.21 [0.51; 1.30]	0,2379	0,004
Feet motor path	Min depth (m)	-0.15 ± 0.04 [-0.16; -0.14]	-0.13 ± 0.04 [-0.14; -0.12]	-0.13 ± 0.03 [-0.14; -0.12]	0.594	0.034
	Max depth (m)	-0.43 ± 0.07 [-0.45; -0.42]	-0.43 ± 0.06 [-0.45; -0.42]	-0.42 ± 0.06 [-0.44; -0.41]	1.840	0.098

	Vertical amplitude (m)	0.28 ± 0.04 [0.27; 0.29]	0.30 ± 0.05 [0.29; 0.32]	0.29 ± 0.04 [0.28; 0.30]	1.842	0.100
	Horizontal amplitude (m)	1.20 ± 0.21 [1.16; 1.24]	1.16 ± 0.22 [1.10; 1.22]	1.12 ± 0.23 [1.05; 1.20]	1.603	0.086
	Medio-lateral amplitude (m)	0.35 ± 0.05 [0.34; 0.36]	0.35 ± 0.07 [0.33; 0.37]	0.35 ± 0.05 [0.34; 0.37]	0.831	0.047
	Horizontality index	1.09 ± 0.25 [1.04; 1.14]	1.10 ± 0.27 [1.02; 1.17]	1.10 ± 0.22 [1.03; 1.17]	3,722	0.057
	Antero-posterior stabilization index in the sagittal plane	1.84 ± 24.26 [-6.80; 3.12]	3.72 ± 23.98 [-3.28; 10.73]	4.89 ± 15.75 [-10.03; 0.26]	2.890	0.045
Head motor path	Min depth (m)	**0.26 ± 0.04[b.c]** [0.25; 0.27]	**0.14 ± 0.08[a.c]** [0.12; 0.16]	**0.26 ± 0.04[a.b]** [0.25; 0.27]	25.096	0.596
	Max depth (m)	**-0.15 ± 0.06[b]** [-0.16; -0.13]	**-0.18 ± 0.05[a.c]** [-0.19; -0.16]	**-0.15 ± 0.05[b]** [-0.16; -0.13]	7.925	0.318
	Vertical amplitude (m)	**0.40 ± 0.09[b]** [0.39; 0.42]	**0.32 ± 0.10[a.c]** [0.29; 0.35]	**0.41 ± 0.07[b]** [0.39; 0.43]	8.919	0.344
	Horizontal amplitude (m)	1.13 ± 0.22 [1.08; 1.17]	1.15 ± 0.22 [1.09; 1.22]	1.11 ± 0.20 [1.04; 1.17]	0.963	0.054
	Horizontal amplitude of the motor path of the head out of the water (m)	**0.63 ± 0.08[b]** [0.62; 0.65]	**0.45 ± 0.10[a.c]** [0.42; 0.48]	**0.62 ± 0.08[b]** [0.60; 0.65]	32.378	0.656
CoM motor path	Min depth (m)	-0.13 ± 0.02 [-0.13; -0.12]	-0.13 ± 0.05 [-0.14; -0.11]	-0.11 ± 0.07 [-0.13; -0.09]	0.672	0.038
	Max depth (m)	-0.23 ± 0.03 [-0.24; -0.23]	-0.23 ± 0.03 [-0.24; -0.23]	-0.23 ± 0.03 [-0.24; -0.22]	1.674	0.090
	Vertical amplitude (m)	0.11 ± 0.02 [0.10; 0.11]	0.11 ± 0.04 [0.09; 0.12]	0.13 ± 0.06 [0.11; 0.14]	3.559	0.173

Horizontal amplitude (m)	1.14 ± 0.20 [1.10; 1.18]	1.15 ± 0.21 [1.08; 1.21]	1.11 ± 0.19 [1.05; 1.17]	0.617	0.035

Table 2. Joint angles (hip, knee, and trunk) measured in relation to the sagittal plane throughout one cycle, and repeated measures ANOVA results.

Variables	**Breathing cycle**	**Non-breathing cycle**	**Breathing cycle following a non-breathing cycle**	**F**	**η^2**
	Mean ± SD [95%CI]	**Mean ± SD [95%CI]**	**Mean ± SD [95%CI]**		
Hip angle (°)	49.80 ± 8.70 [48.00; 51.60]	50.90 ± 7.60 [48.70; 53.10]	50.80 ± 7.50 [48.40; 53.30]	0.852	0.048
Knee angle (°)	137.00 ± 10.10 [134.90; 139.00]	141.00 ± 11.90 [137.50; 144.50]	141.10 ± 10.2 [137.80; 144.50]	0.532	0.030
Thorax angle (°)	44.10 ± 9.70 [42.10; 46.10]	45.00 ± 13.30 [41.20; 48.90]	47.10 ± 11.5 [43.30; 50.90]	1.195	0.066

CoM- center of mass; v – velocity; [a] – differs from the breathing cycle; [b] - differs from the non-breathing cycle; [c] - differs from the breathing cycle following a non-breathing cycle.

Table 3. Three-dimensional velocities of the CoM, feet, hands, and head, considering maximum, mean, and minimum values in each direction, and repeated measures ANOVA results.

Variables			**Breathing cycle**	**Non-breathing cycle**	**Breathing cycle following a non-breathing cycle**	**F**	**η^2**
			Mean ± SD [95%CI]	**Mean ± SD [95%CI]**	**Mean ± SD [95%CI]**		
Hand	**Max**	**X**	1.39 ± 0.47 [1.29; 1.49]	1.47 ± 0.26 [1.39; 1.54]	1.38 ± 0.2 [1.31; 1.44]	3.039	0.152
		Y	2.54 ± 0.84 [2.36; 2.71]	2.61 ± 0.61 [2.43; 2.79]	2.54 ± 0.61 [2.34; 2.74]	1.847	0.098
		Z	1.64 ± 0.61 [1.52; 1.77]	1.65 ± 0.47 [1.51; 1.79]	1.7 ± 0.43 [1.56; 1.84]	0.783	0.044

	Mean	X	-0.01 ± 0.03 [-0.02; -0.01]	-0.01 ± 0.03 [-0.02; 0]	0 ± 0.02 [-0.01; 0]	0.861	0.048
		Y	0.93 ± 0.14 [0.90; 0.96]	0.95 ± 0.13 [0.91; 0.98]	0.93 ± 0.12 [0.89; 0.97]	1.263	0.069
		Z	0 ± 0.04 [-0.01; 0.01]	0 ± 0.04 [-0.02; 0.01]	0 ± 0.04 [-0.01; 0.01]	0.058	0.003
	Min	X	-1.92; 0.34 [-1.99; -1.85]	-1.99; 0.36 [-2.09; -1.88]	-1.88; 0.31 [-1.98; -1.78]	2.973	0.149
		Y	-0.85 ± 0.25 [-0.90; -0.80]	-0.96 ± 0.27 [-1.04; -0.88]	-0.95 ± 0.23 [-1.03; -0.88]	0.698	0.039
		Z	-1.25 ± 0.25 [-1.31; -1.20]	-1.26 ± 0.25 [-1.33; -1.19]	-1.22 ± 0.16 [-1.27; -1.17]	0.928	0.052
Feet	Max	X	1.26 ± 0.25 [1.21; 1.31]	1.36 ± 0.25 [1.28; 1.43]	1.34 ± 0.21 [1.27; 1.41]	0.612	0.035
		Y	2.32 ± 0.29 [2.26; 2.38]	2.36 ± 0.26 [2.28; 2.44]	2.32 ± 0.26 [2.24; 2.41]	3.772	0.180
		Z	**0.77 ± 0.27**^{b} [0.71; 0.82]	**0.98 ± 0.35**$^{a.c}$ [0.88; 1.08]	**0.81 ± 0.29**^{b} [0.72; 0.91]	4.482	0.209
	Mean	X	-0.01 ± 0.1 [-0.03; 0.01]	-0.01 ± 0.1 [-0.04; 0.02]	0.01 ± 0.07 [-0.01; 0.03]	1.127	0.062
		Y	1.01 ± 0.20 [0.97; 1.05]	0.98 ± 0.20 [0.92; 1.04]	0.94 ± 0.18 [0.88; 1.00]	3.046	0.152
		Z	0.04 ± 0.1 [0.02; 0.06]	**0.03 ± 0.09**^{c} [0.01; 0.06]	**-0.01 ± 0.07**^{b} [-0.04; 0.01]	5.496	0.244
	Min	X	-1.46 ± 0.33 [-1.53; -1.40]	-1.57 ± 0.39 [-1.68; -1.46]	-1.5 ± 0.28 [-1.59; -1.41]	0.934	0.052
		Y	-1.54 ± 0.61	-1.76 ± 0.53	-1.75 ± 0.54	1.696	0.091

			[-1.66; -1.41]	[-1.91; -1.6]	[-1.93; -1.58]		
		Z	-1.64 ± 0.47 [-1.73; -1.54]	-1.85 ± 0.54 [-2.01; -1.70]	-1.82 ± 0.38 [-1.95; -1.69]	3.613	0.175
Head	Max	X	0.12 ± 0.07 [0.10; 0.13]	0.12 ± 0.08 [0.10; 0.15]	0.13 ± 0.08 [0.10; 0.15]	0.612	0.035
		Y	1.27 ± 0.23 [1.23; 1.32]	1.30 ± 0.17 [1.25; 1.35]	1.31 ± 0.23 [1.23; 1.38]	0.284	0.016
		Z	1.17; 0.26 [1.12; 1.22]	**1.01; 0.3[c]** [0.92; 1.10]	**1.20 ± 0.25[b]** [1.12; 1.28]	3.830	0.184
	Mean	X	**0.02 ± 0.03[b]** [0.01; 0.02]	**0.02 ± 0.04[a]** [0.01; 0.03]	0.02 ± 0.04 [0.01; 0.03]	3.726	0.180
		Y	0.94 ± 0.14 [0.91; 0.97]	**0.97 ± 0.13[c]** [0.93; 1.00]	**0.93 ± 0.13[b]** [0.88; 0.97]	4.101	0.194
		Z	0.02 ± 0.06 [0; 0.03]	-0.01 ± 0.09 [-0.04; 0.01]	0.02 ± 0.07 [0; 0.04]	1.166	0.064
	Min	X	-0.07 ± 0.06 [-0.09; -0.06]	-0.08 ± 0.05 [-0.1; -0.07]	-0.08 ± 0.04 [-0.09; -0.07]	3.083	0.154
		Y	0.58 ± 0.13 [0.55; 0.60]	0.53 ± 0.17 [0.48; 0.58]	0.53 ± 0.16 [0.48; 0.59]	1.615	0.087
		Z	-1.25 ± 0.39 [-1.33; -1.17]	**-1.06 ± 0.37[c]** [-1.17; -0.96]	**-1.32 ± 0.33[b]** [-1.43; -1.22]	3.507	0.171
CoM	Max	X	0.06 ± 0.04 [0.05; 0.07]	0.07 ± 0.04 [0.05; 0.08]	0.07 ± 0.04 [0.05; 0.08]	1.290	0.071
		Y	**1.24 ± 0.17[b]** [1.21; 1.27]	**1.30 ± 0.18[a,c]** [1.25; 1.35]	**1.24 ± 0.16[b]** [1.18; 1.29]	7.180	0.297
		Z	0.30 ± 0.06 [0.29; 0.31]	0.32 ± 0.07 [0.29; 0.34]	0.32 ± 0.07 [0.30; 0.34]	3.090	0.154

	X	0.01 ± 0.04 [0.01; 0.02]	0.01 ± 0.03 [0.01; 0.02]	0.02 ± 0.04 [0.01; 0.03]	3.124	0.155
Mean	**Y**	0.94 ± 0.14 [0.91; 0.97]	0.96 ± 0.13 [0.92; 1.00]	0.93 ± 0.13 [0.89; 0.97]	2.459	0.126
	Z	-0.01 ± 0.07 [-0.02; 0.01]	0 ± 0.03 [-0.01; 0]	0 ± 0.02 [-0.01; 0]	0.570	0.032
	X	**-0.02 ± 0.04[b,c]** [-0.03; -0.02]	**-0.04 ± 0.04[a]** [-0.05; -0.02]	**-0.04 ± 0.04[a]** [-0.05; -0.02]	6.094	0.264
Min	**Y**	0.51 ± 0.12 [0.48; 0.54]	0.50 ± 0.14 [0.46; 0.54]	0.49 ± 0.13 [0.45; 0.54]	0.884	0.049
	Z	**-0.36 ± 0.07[c]** [-0.38; -0.35]	-0.38 ± 0.09 [-0.40; -0.35]	**-0.43 ± 0.11[a]** [-0.46; -0.39]	5.931	0.259

CoM- center of mass; v – velocity; [a] – differs from the breathing cycle; [b] - differs from the non-breathing cycle; [c] - differs from the breathing cycle following a non-breathing cycle.

Table 4 – Intra-cycle mean velocity variation, fractal dimension and repeated measures ANOVA results.

Variables	**Breathing cycle** Mean ± SD [95%CI]	**Non-breathing cycle** Mean ± SD [95%CI]	**Breathing cycle following a non-breathing cycle** Mean ± SD [95%CI]	**F**	**η^2**
Coefficient of variation of velocity of CoM (%)	4.43 ± 6.77 [1.01; 7.86]	3.74 ± 4.38 [1.53; 5.96]	4.45 ± 5.51 [1.34; 7.57]	0.275	0.052
Fractal dimension	1.269 ± 0.095 [1.249; 1.288]	1.291 ± 0.095 [1.264; 1.319]	1.313 ± 0.079 [1.287; 1.339]	0.891	0.050

CoM- center of mass; v – velocity; [a] – differs from the breathing cycle; [b] - differs from the non-breathing cycle; [c] - differs from the breathing cycle following a non-breathing cycle.

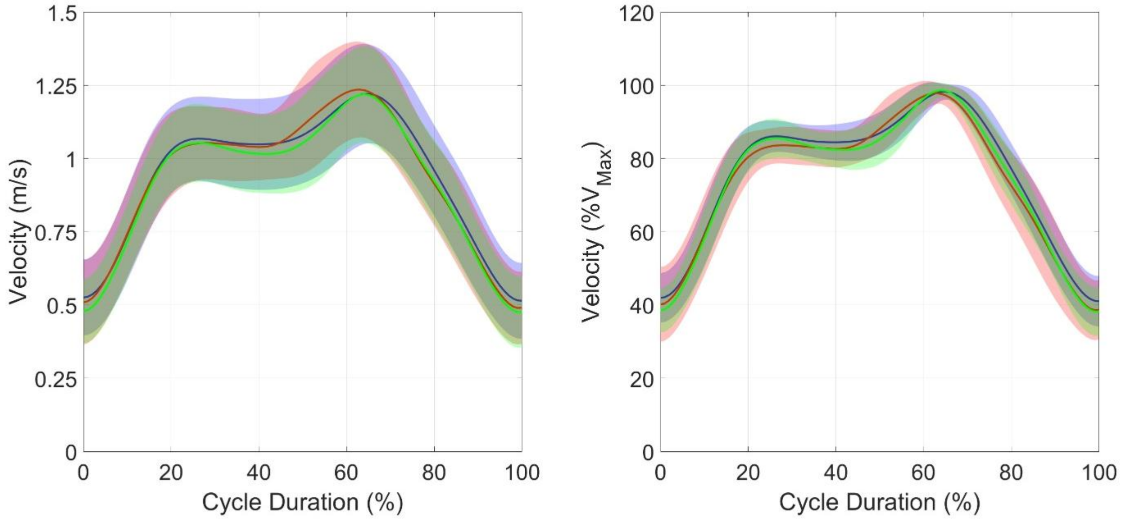


Figure 2. Mean group curves ± SD and SPM ANOVA test results. In the left panel, velocity values are presented in absolute values, while in the right panel, they are normalized as a percentage of the cycle maximum velocity. Blue: breathing cycle; Red: non-breathing cycle; Green: breathing cycle following a non-breathing cycle.

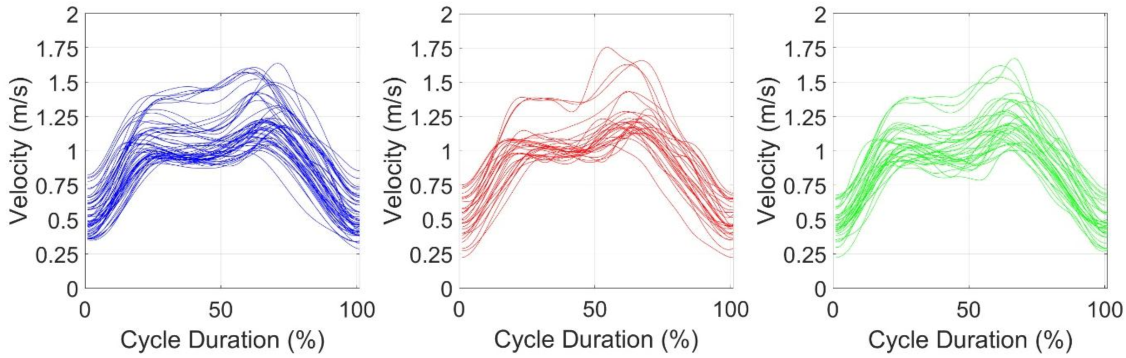


Figure 3. Overlapping representation of all recorded breathing cycles. Blue: breathing cycle; Red: non-breathing cycle; Green: breathing cycle following a non-breathing cycle.

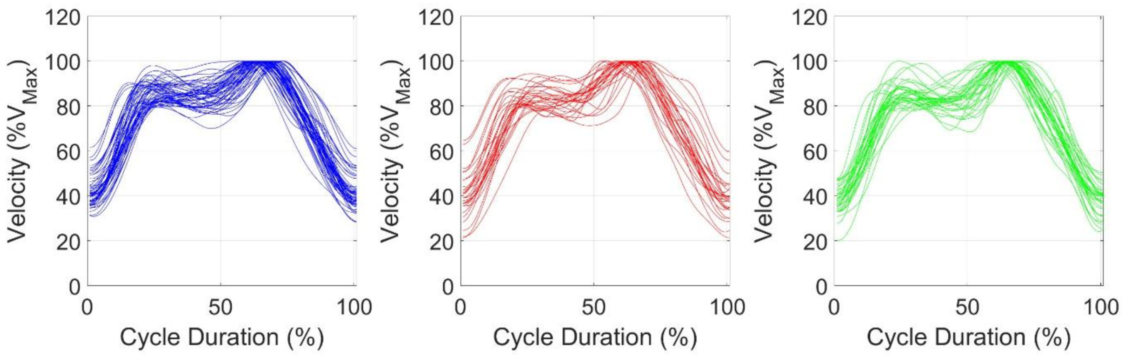


Figure 4. Overlapping representation of all recorded cycles. Velocity was normalized as a percentage of the cycle's maximum values. Blue: breathing cycle; Red: non-breathing cycle; Green: breathing cycle following a non-breathing cycle.

4. Discussion

The current study characterized and compared two breaststroke breathing patterns: breathing every cycle and breathing every two cycles. Additionally, we aimed to analyze and compare dv and FD between these two breathing patterns. We hypothesized that the non-breathing cycle would be associated with changes in kinematics compared to the breathing cycle. Furthermore, we hypothesized that a reduced breathing pattern would lead to lower dv and reduced FD. Our main results showed that the non-breathing cycle had both the minimum and the highest maximum head depths, the lowest horizontal amplitude of the head's motor path out of the water and the smallest vertical head amplitude. This cycle also presented the highest maximum vertical velocity of the feet which may have led to also presenting the highest maximum CoM velocity in the swimming direction compared to the other two cycle types. Lastly, the breathing cycle showed greater medio-lateral hand amplitude and a lower minimum CoM velocity than the breathing cycle following a non-breathing cycle.

This is the first study to examine the kinematic influence of different breathing patterns in breaststroke. Our findings indicate that the breathing cycle and the breathing cycle following a non-breathing cycle exhibited higher minimum and lower maximum head depths than the non-breathing cycle. This means that, although the non-breathing cycle showed head positions closest to the water surface level when the head was out of the water, it also exhibited the deepest positions when submerged. This was expected, as the swimmers did not lift their heads out of the water to breathe. However, it appears that not breathing causes the head to sink more during a swimming cycle than when swimmers lift their heads for breathing. The non-breathing cycle also showed the lowest vertical head amplitude, along with the lowest horizontal amplitude of the head above the water. This aligns with expectations, as in the non-breathing cycle, swimmers only break the water's surface minimally to avoid disqualification. According to World Aquatics rules, swimmers are required to break the surface with their head but it is not mandatory to breathe during this phase.

When swimmers breathe, their head rises slightly above the water surface, potentially increasing vertical displacement compared to the non-breathing cycle, where the head re-mains closer to the water level for longer periods. Lifting the head for breathing could also increase hydrodynamic drag by increasing the cross-sectional frontal area (Kjendlie & Stallman, 2008). A less streamlined position may lead not only to increased drag but also to a higher energy cost (Chatard et al., 1985, 1990; Kjendlie et al., 2004a, b).

However, the thorax angle in our study did not differ between the three types of cycles, and no changes in active drag between two breathing patterns in breaststroke were found in 13m maximal bouts (Alves et al., 2024). This may be due to the fact that the breaststroke technique has become flatter over the years compared to 20-40 years ago, and therefore the action of not breathing does not affect the trunk inclination. For instance, previous studies reported angles of 53° and 63° for more undulating styles (Persyn et al., 2005; Sanders, 1996), while this study observed angles of 45° ± 12°, which is consistent with more recent research (Gourgoulis et al., 2018; Seifert et al., 2014).

The non-breathing cycle also showed a higher mean head velocity in the swimming direction compared to the breathing cycle following a non-breathing cycle. This may be because not lifting the head reduces vertical displacement, allowing swimmers to maintain higher forward velocity. By avoiding the interruption caused by head elevation for breathing, the swimmer may sustain a more continuous propulsion phase, which could contribute to maintaining velocity.

The non-breathing cycle exhibited the highest maximum CoM velocity in the swimming direction, and a higher maximum vertical velocity of the feet, suggesting that not breathing may enhance feet propulsion and, consequently, peak CoM velocity. However, despite achieving higher peak velocities, the overall mean and minimum velocities of the CoM were unaffected. One possible explanation for this is that while the swimmer achieves higher velocities during the non-breathing phase, the rest of the cycle brings the velocity back to similar levels as the other cycles. This is further supported by the absence of differences in mean CoM velocity in the swimming direction in both the SPM analysis and dv.

The medio-lateral hand amplitude was greater in the breathing cycle, along with a lower minimum vertical velocity of the CoM, compared to the breathing cycle following a non-breathing cycle. This suggests that swimmers in the breathing cycle achieve a larger medio-lateral hand amplitude, which could contribute to increased propulsion. Additionally, it indicates that not breathing in the previous cycle may influence the subsequent breathing cycle by reducing medio-lateral hand amplitude, potentially diminishing propulsion. The lower minimum vertical velocity of the CoM in the breathing cycle suggests that this cycle may experience a greater velocity drop, potentially due to the increased drag caused by the elevated head position during breathing. This effect, though, did not reflect in the dv, which remained similar across cycles.

Intracycle velocity variation is a biomechanical variable that reflects the velocity fluctuation within a swimming cycle (Barbosa et al., 2013; Vilas-Boas, 2011). However, the literature presents conflicting results, reporting both higher and lower dv values in elite swimmers. One study concluded that the coefficient of variation was the only approach sensitive to both mean swimming velocity and instantaneous velocity dispersion within the cycle (Figueiredo et al., 2013). However, as highlighted by Gonjo et al. (2024), the co-efficient of variation should not be directly compared without accounting for the mean velocity, as differences in mean velocity can influence dv comparisons and lead to misinterpretations. When using the coefficient of variation as an index of dv, researchers and practitioners should always report and interpret the coefficient of variation alongside the mean and standard deviation to ensure accurate conclusions and meaningful feedback.

In breaststroke, previous studies reported dv values of 32% for male breaststrokers (Gourgoulis et al., 2018) and 44.2 ± 2.4% and 48.5 ± 2.5% for elite and national-level breaststroke swimmers, respectively (Fernandes et al., 2024). In our study, values ranged between 1.01% and 27.9%, with no differences between the three breathing cycle types. These relatively low coefficient of variation values may be attributed to the fact that the sample in this study includes young swimmers with a relatively low competitive level. As a result, they may lack the ability to generate significant accelerations, which could lead to lower dv. Furthermore, the three cycle types exhibited similar velocity variation, suggesting that the breathing pattern did not influence dv.

Recent studies have incorporated non-linear analyses, such as *FD*, to assess motion complexity in cyclic sports. Altogether, higher *FD* values indicate greater complexity in the time series (Bravi et al., 2011). In our study, *FD* was calculated with the Higuchi's method, as it seems to be the most suitable for research involving time series (Castiglioni et al., 2011). Reported *FD* values in front crawl range from approximately 1.84 to 1.95 (Barbosa et al., 2016, 2017a), with values of 1.94–1.95 observed before and after a front crawl bout. A broader analysis across all four swimming techniques found *FD* values between 1.82 and 1.92, with breaststroke showing the highest complexity (*FD* = 1.92) (Barbosa et al., 2016). Our *FD* values ranged from 1.11 to 1.55, with no differences between the three cycle types, suggesting similar complexity among them. These lower values compared to the literature may be attributed to the high variability within the sample, which could stem from differences in skill level and technique across the recruited swimmers. In fact, highly qualified, expert, and non-expert swimmers exhibited

FD values of 1.84 ± 0.08, 1.85 ± 0.09, and 1.89 ± 0.06, respectively, showing that the level of expertise affect the complexity of the motor system (Barbosa et al., 2017b).

Regarding the SPM analysis, the mean velocity curves were similar across the three types of cycles, pointing out to similar patterns. This suggests that, despite some kinematic differences, the overall cycle remain consistent and, as seen above, with much lower complexity than expected. By observing the overlapping representation of all recorded breathing cycles, it becomes clear that swimmer's ability to swim faster has a significant impact on the results, with lower-velocity and higher-velocity cycles differences becoming visible (Figure 3). By normalizing each cycle to its maximum velocity, this effect was tackled. Nevertheless, this also highlights that swimmers reached their maximum velocity at different moments in time, leading to an overlapping effect at the top of the graph similar to a horizontal line. Indeed, the time of occurrence of the maximum and minimum velocities within the swimming cycle were not studied. However, this might be relevant, as it will relate to the swimming technique and the body position.

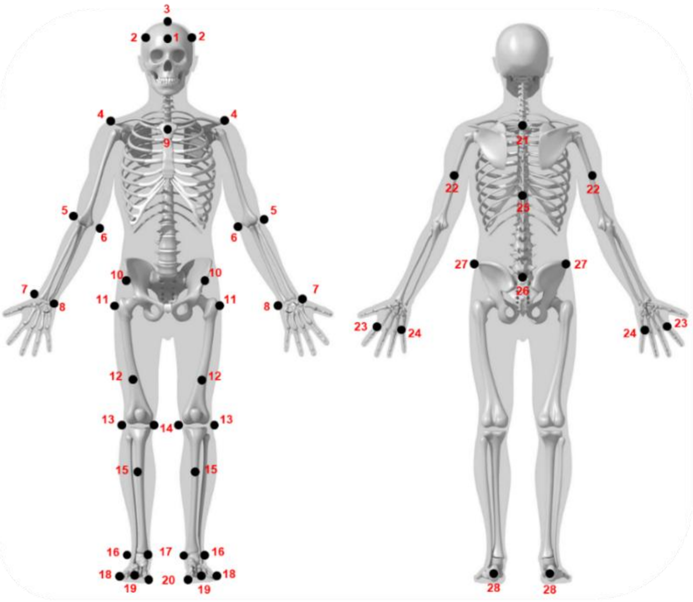
5. Limitations and Future Research

This study focused on three specific cycle types, limiting the scope of analysis to these predefined breathing patterns. Future research should explore additional breathing patterns, such as breathing every three cycles. Another key limitation was the variability within the sample, which may have influenced the results. A more homogeneous sample, such as elite swimmers with similar technical proficiency, could provide more consistent insights into the effects of such a detailed aspect of technique, as different breathing patterns. Additionally, the sample size did not allow for the investigation of potential sex-related differences in the response to breathing strategies, which should be addressed in future studies. Furthermore, breathing pattern strategies over longer distances were not addressed in this study, as performance was analyzed at the cycle level rather than across the full 25 m trials or other distances. Future studies should investigate the impact of breathing frequency across longer race distances.

6. Conclusions

This is the first study on the influence of different breathing patterns in the breast-stroke technique on the kinematics and non-linear complexity of the swimmer's movement. Differences between the three breaststroke swimming modes were minimal, and not clearly pointing to the superiority of one of the breathing techniques. Nevertheless, when not breathing, the swimmer kept the head closer to the water level when above the water, but also furthest when inside it, while exhibiting the lowest horizontal amplitude of the head out of the water and vertical amplitude of the overall movement of the head. Additionally, this cycle presented the highest maximum vertical velocity of the feet and the highest maximal CoM velocity in the swimming direction, data that may suggest a relative biomechanical superiority. Finally, the breathing cycle showed greater medio-lateral hand amplitude and a lower minimum CoM horizontal velocity than the breathing cycle following a non-breathing cycle.

Appendix A

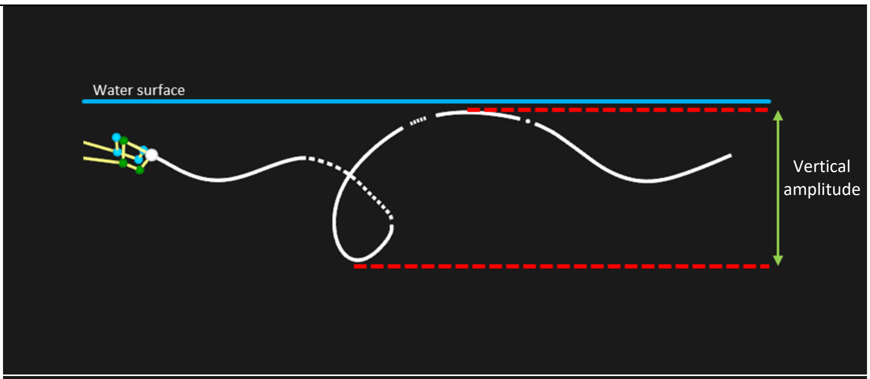
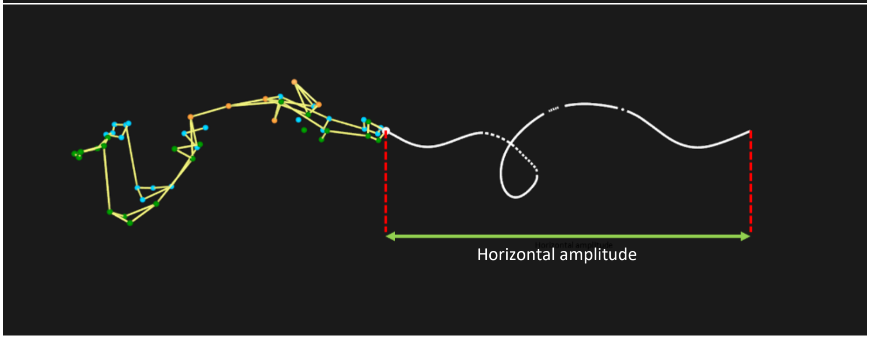


#	Marker Name	Description
1	**HeadFront**	Forehead, above the nose.
2	**HeadL, HeadR**	Just above the ear center.
3	**HeadFront**	On top of the head vertically above the ears.
4	**LShoulderTop, RShoulderTop**	On top of the shoulder (bony prominence).
5	**LElbowOut, RElbowOut**	On the outside of the elbow (bony prominence).
6	**LElbowIn, RElbowIn**	On the inside of the elbow (bony prominence).
7	**LWristIn, RWristIn**	On the inside of the wrist (bony prominence on the thumb side).
8	**LWristOut, RWristOut**	On the outside of the wrist (bony prominence on the pinky side).
9	**Chest**	Upper part of the sternum.
10	**WaistLFront, WaistRFront**	On the front of the pelvis (bony prominence).
11	**LThighFrontHigh, RThighFrontHigh**	Top of the thigh.
12	**LThighFrontLow, RThighFrontLow**	Above the kneecap.
13	**LKneeOut, RKneeOut**	On the outside of the knee (bony prominence).
14	**LKneeIn, RKneeIn**	On the inside of the knee (bony prominence).
15	**LShinFrontHigh, RShinFrontHigh**	Front of the shin.
16	**LAnkleOut, RAnkleOut**	On the outside of the ankle.
17	**LAnkleIn, RAnkleIn**	On the inside of the ankle.
18	**LForefoot5, RForefoot5**	Base of the toes on the outside.
19	**LForefoot2, RForefoot2**	Top of the foot tip.

20	**LForefoot1, RForefoot1**	Base of the toes on the inside.
21	**SpineThoracic2**	On the 2nd prominence below the biggest prominence on the top of the spine.
22	**LArm, RArm**	On the back of the upper arm.
23	**LHand2, RHand2**	Just below the index finger's knuckle.
24	**LHand5, RHand5**	Just below the pinky finger's knuckle.
25	**SpineThoracic12**	A few cm below the midpoint of the lower tip of the shoulder blades.
26	**WaistBack**	On the midpoint between the two prominences on the back of the pelvis.
27	**WaistL, WaistR**	On the sides of the pelvis (bony prominence).
28	**LHeelBack, RHeelBack**	Back of the heel.

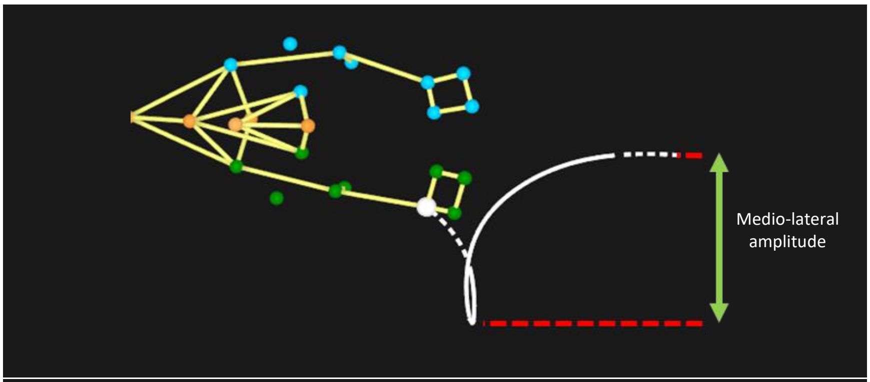
Note: the prefix "L" and "R" denote Left and Right side

Appendix B

Variables	Schematic presentation
	Hand variables
1. Vertical amplitude of the hand motor path during one upper limbs´ full cycle. Measured between the shallowest and deepest point of the hand motor path during one upper limbs´ full cycle.	
2. Horizontal amplitude of the hand motor path during one upper limbs´ full cycle. Measured between the most rearward and forward point of the hand motor path during one upper limbs´ full cycle.	

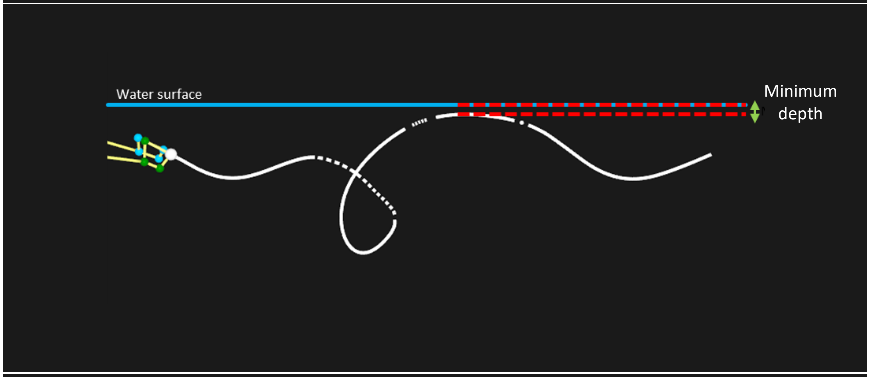
3. Medio-lateral amplitude of the hand motor path during one upper limbs´ full cycle.

Measured between the start of outsweep and start of insweep during one upper limbs´ full cycle.



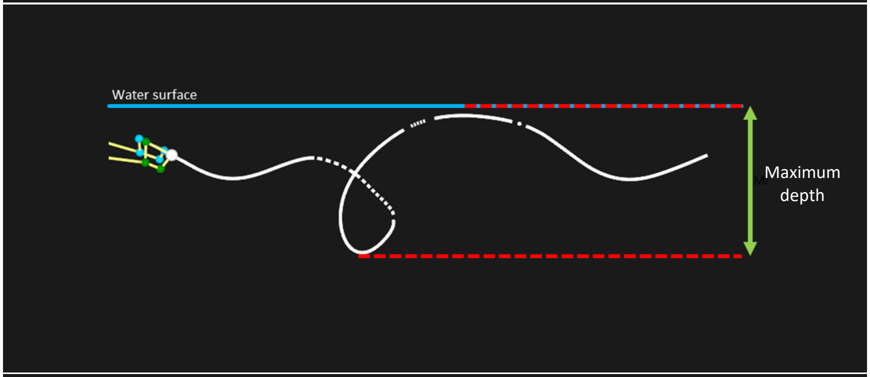
4. Minimum depth of the hand motor path during one upper limbs´ full cycle.

Measured between the water surface and the shallowest point of the hand motor path during one upper limbs´ full cycle.



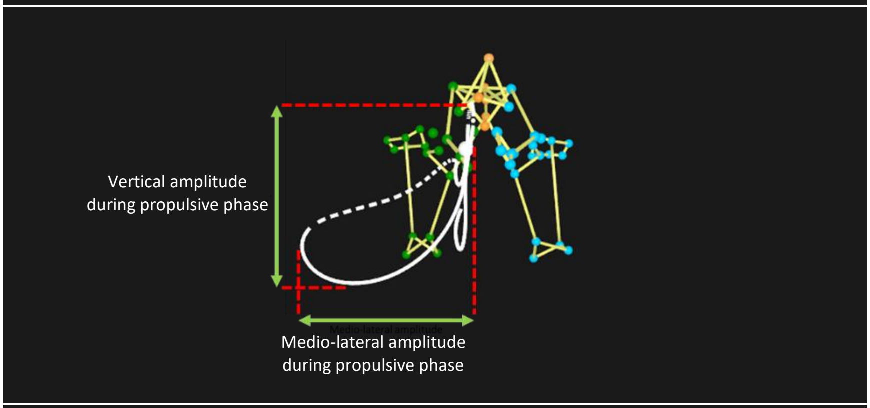
5. Maximum depth of the hand motor path during one upper limbs´ full cycle.

Measured between the water surface and the deepest point of the hand motor path during one upper limbs´ full cycle.



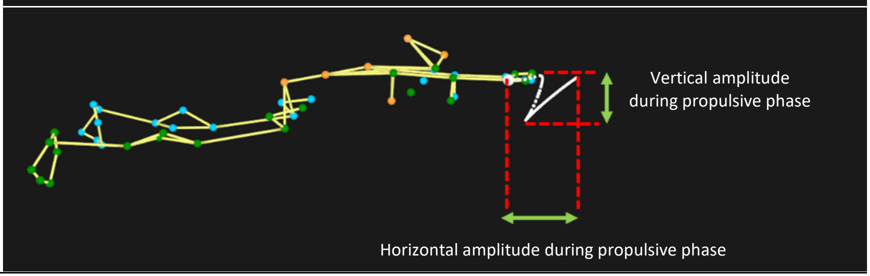
6. Horizontality index of the hand motor path.

Ratio between the medio-lateral amplitude of hand motor path and the vertical amplitude of the hand motor path during the propulsive phase of one upper limbs´ full cycle.



7. Antero-posterior stabilization index of the hand motor path in the sagittal plane.

Ratio between the vertical amplitude of the hand motor path

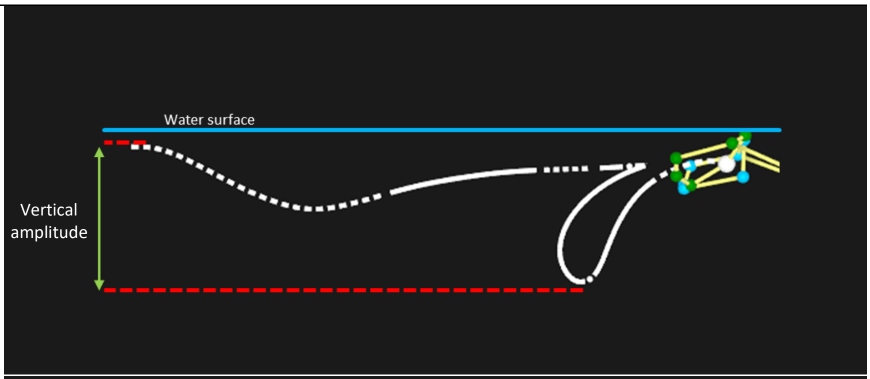


and the horizontal amplitude of the hand motor path during the propulsive phase of one upper limbs´ full cycle.

Foot variables

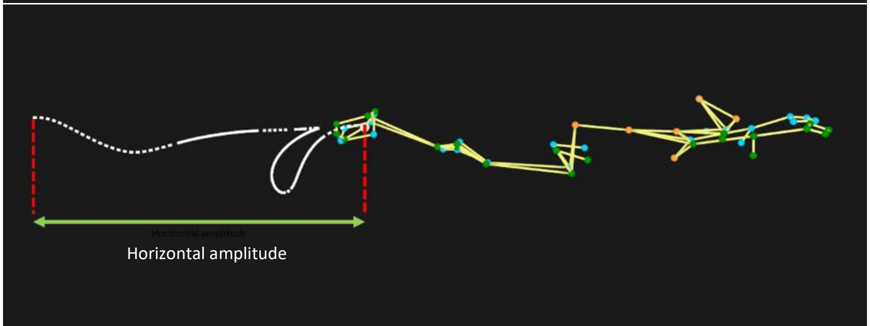
8. Vertical amplitude of the foot motor path during one full lower limbs´ cycle.

Measured between the shallowest and deepest point of the foot motor path during one full lower limbs´ cycle.



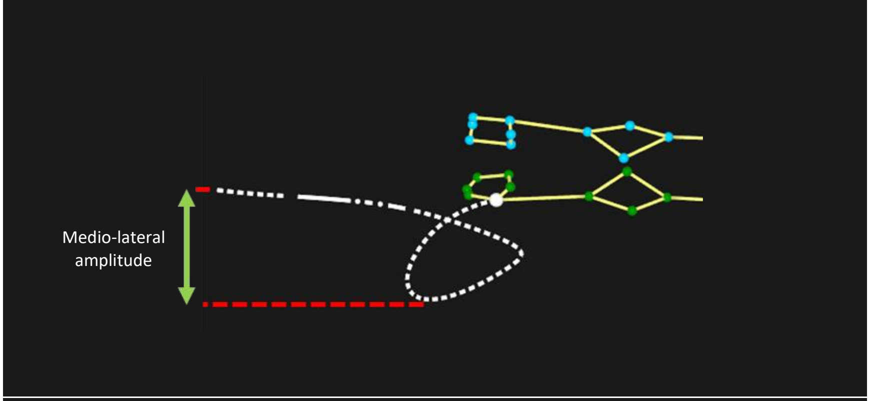
9. Horizontal amplitude of the foot motor path during one full lower limbs´ cycle.

Measured between the most rearward and forward point of the foot path during one full lower limbs´ cycle.



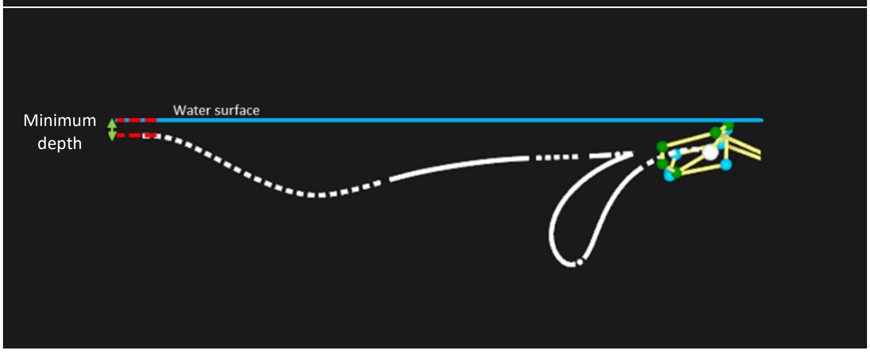
10. Medio-lateral amplitude of the foot motor path during one full lower limbs´ cycle.

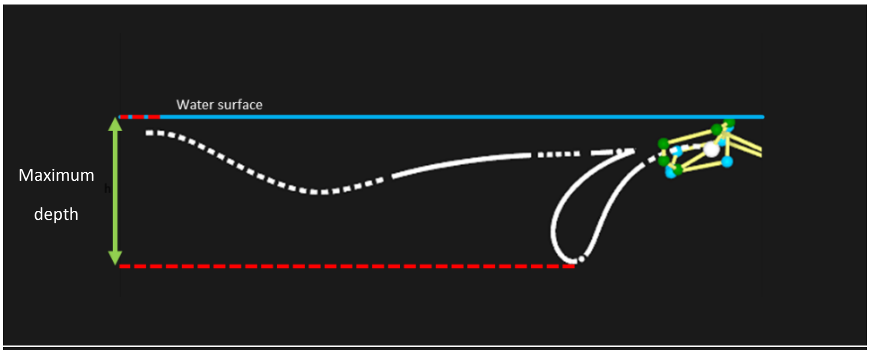
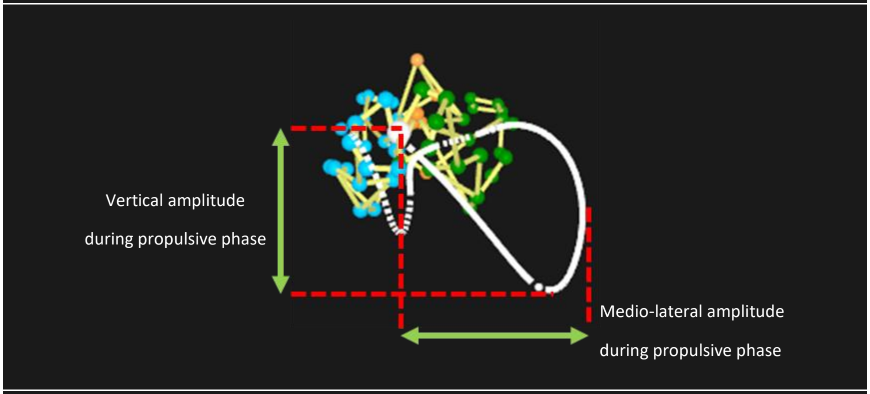
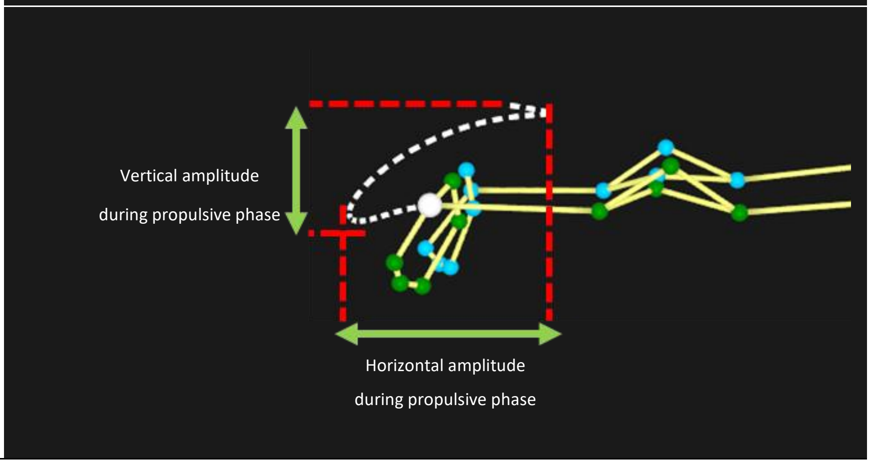
Measured between the start of outsweep and the most lateral point of the motor path during one full lower limbs´ cycle.



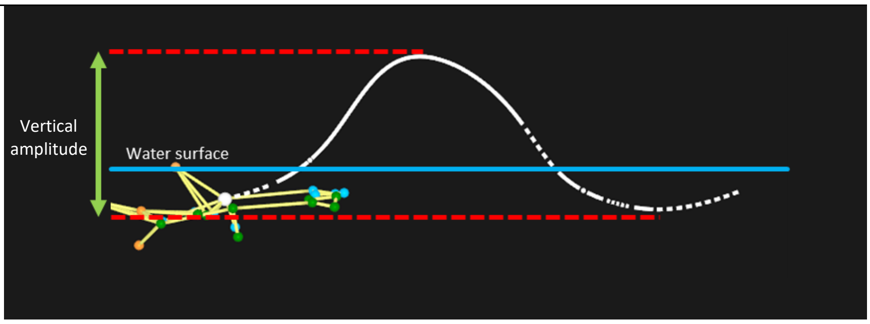
11. Minimum depth of the foot motor path during one full lower limbs´ cycle.

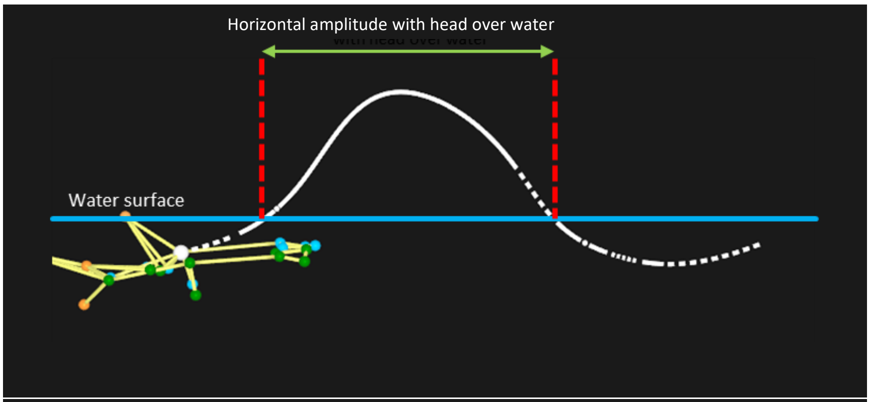
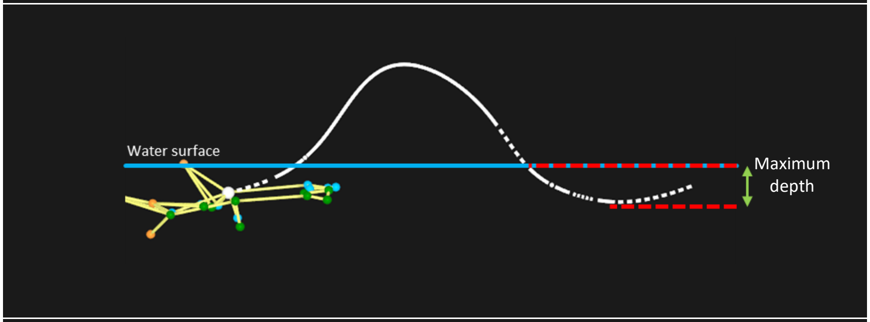
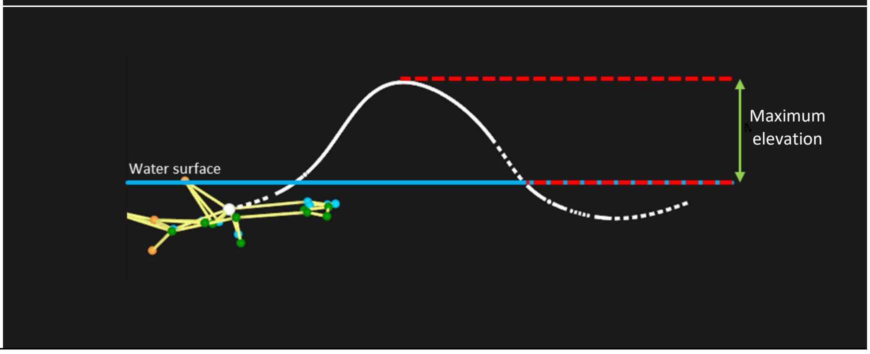
Measured between the water surface and the shallowest point of the foot motor path during one full lower limbs´ cycle.



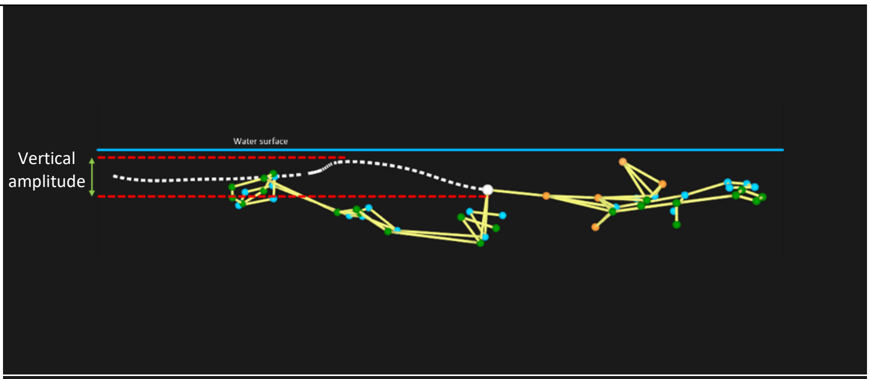
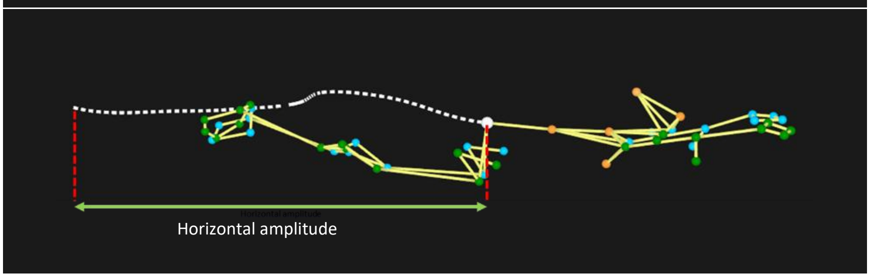
12. Maximum depth of the foot motor path during one full lower limbs´ cycle. Measured between the water surface and the deepest point of the foot motor path during one full lower limbs cycle.	
13. Horizontality index of the foot motor path. Ratio between the medio-lateral amplitude of foot motor path and the vertical amplitude of the foot motor path during the propulsive phase of one full lower limbs cycle.	
14. Antero-posterior stabilization index of the foot motor path in the sagittal plane. Ratio between the vertical amplitude of the foot motor path and the horizontal amplitude of the foot motor path during during the propulsive phase of one full lower limbs cycle.	

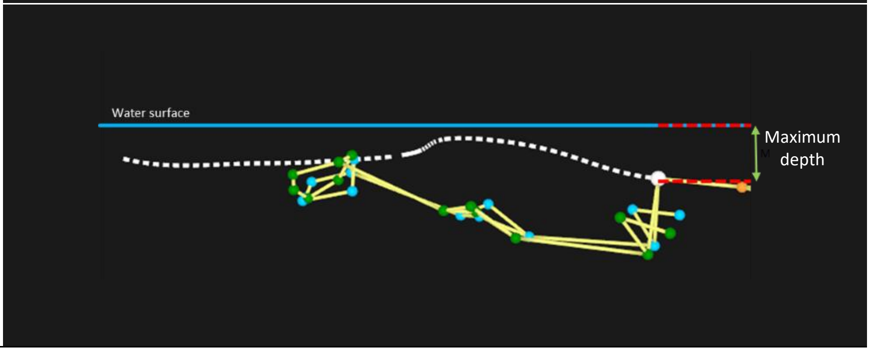
Head variables

15. Vertical amplitude of the head motor path during one full cycle. Measured between the shallowest and deepest point of the head motor path during one full cycle.	

16. Horizontal amplitude of the motor path of the head out of the water during one full cycle. Measured between the rearmost and foremost points of the head out of the water during a complete cycle.	
17. Maximum depth of the head motor path during one full cycle. Measured between the water surface and the deepest point of the head motor path during one full cycle.	
18. Maximum elevation of the head motor path during one full cycle. Measured between the water surface and the highest point above the water of the head motor path during one full cycle.	

Center of mass variables

19. Vertical amplitude of the center of mass motor path during one full cycle. Measured between the shallowest and deepest point of the center of mass motor path during one full cycle.	
20. Horizontal amplitude of the center of mass motor path during one full cycle. Measured between the most rearward and forward point of the	

center of mass during one full cycle.	
21. Maximum depth of the center of mass motor path during one full cycle. Measured between the water surface and the deepest point of the center of mass motor path during one full cycle.	

Chapter 6. Determinants of breaststroke performance: the interplay of efficiency, active drag, and energy cost

Miriam Alves*[1,2,3], Pedro Fonseca[2,3], Leandro Machado[1,2,3], Filipa Sousa[1,2,3], Mário J. Costa[1,2,3], Susana Soares[1,2,3], Ricardo Fernandes[1,2,3], Tiago M. Barbosa[4,5], João Paulo Vilas-Boas[1,2,3]

[1] Centre for Sports Research, Education, Innovation and Intervention in Sport (CIFI2D);

[2] Porto Biomechanics Laboratory (LABIOMEP-UP);

[3] Faculty of Sport, University of Porto, 4200-450 Porto, Portugal;

[4] Department of Sport Sciences, Instituto Politécnico de Bragança, 5300-252 Bragança, Portugal;

[5] Research Centre for Active Living and Wellbeing (LiveWell), Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal

Abstract

Performance in breaststroke is influenced by the swimmer's total energy input and the efficiency with which this energy is converted into forward motion while overcoming hydrodynamic drag. Due to limited research on efficiency and motor path stabilization in breaststroke, particularly regarding the impact of different breathing patterns, this study investigated propulsive efficiency and motor path stabilization by comparing two breathing patterns (breathing every cycle versus every two cycles) and examining their relationships with energy cost and active drag. Efficiency during a breaststroke cycle was quantified using the ratio between the swimmer's center of mass velocity and the velocity of the propulsive segments. Motor stabilization indices were obtained considering antero-posterior, medio-lateral and vertical movement amplitudes. Partial correlations controlling for velocity were performed to explore associations between these variables, energy cost and active drag. Results showed that breathing every cycle improved hands efficiency (0.67 ± 0.04 vs. 0.64 ± 0.04), while breathing every two cycles enhanced feet stabilization (0.47 ± 0.12 vs. 0.51 ± 0.12) and displacement (-0.13 ± 0.16 vs. -0.07 ± 0.16). Moreover, higher motor path stabilization was linked to lower energy cost, and feet and total stabilization indices demonstrated strong relations with feet displacement, underlining their role in propulsion effectiveness. This study introduced novel indices to assess breaststroke efficiency continuously across one swimming cycle, including hand, foot, and global measures, along with motor path stabilization indices

KEY WORDS: BREATHING PATTERNS; KINEMATICS; MOTOR PATH STABILIZATION

1. Introduction

The goal of a competitive swimmer is to cover a given distance in the shortest possible time. Swimming is characterized by the intermittent application of propulsive force to overcome velocity-dependent hydrodynamic drag. Propulsion arises from the combined action of the upper limbs, lower limbs and trunk, which depends on the swimmer's technique. Technique can significantly influence the energy cost (C) of swimming (di Prampero, 1986), defined as the ratio between metabolic power and swimming velocity $\left(C = \dot{E}_{tot}/v\right)$, highlighting the critical role of biomechanics and physiology in performance. Moreover, di Prampero et al. (1974) described a general equation of swimmer's performance (Equation 1), where v represents velocity, $\dot{E}_{tot}$ metabolic power, η_d total mechanical propulsive efficiency (ratio between useful mechanical power and metabolic power) and D_a is the hydrodynamic drag:

$$v = \dot{E}_{tot} \times \frac{\eta_d}{D_a} \Leftrightarrow v = \frac{\dot{E}_{tot}}{C} \tag{1}$$

According to this model, performance is influenced by the swimmer's total energy input (aerobic and anaerobic) and the efficiency with which this energy is converted into forward motion against D_a. Therefore, performance reflects the energy available to the system, the efficiency of the energy transformation process and the magnitude of the drag force opposing movement (Ribeiro et al., 2017; Vilas-Boas, 2000). From equation 1 and the definition of C one has $C = D_a/\eta_d$ and $v = \dot{E}_{tot}/C$. Hence, for a given metabolic power ($\dot{E}_{tot}$), a swimmer with high propelling efficiency and low drag (i.e. low C) will outperform one with lower efficiency and higher drag (Komar et al., 2012). Conversely, a swimmer with greater energy availability (higher $\dot{E}_{tot}$) may compensate for higher C and still achieve better performance (di Prampero et al., 2010). In summary, swimming performance depends on propelling efficiency, drag reduction and energy supply (see also Figueiredo et al., 2012; Mezencio et al, 2020).

Hydrodynamic drag can be assessed in two ways: (i) passive drag, measured when the swimmer provides no propulsion, normally lying in the fundamental hydrodynamic position while being towed; and (ii) active drag (D_a), which refers to the experienced water resistance during swimming motion (Clarys, 1979). One widely used method to estimate resistive forces is the Velocity Perturbation Method (VPM) (Kolmogorov & Duplishcheva, 1992) capable of measuring D_a in all swimming techniques. VPM is based on the assumption that swimmers can perform repeated sprint trials with the same maximal mechanical power output. In this method, the swimmer performs two maximal-effort trials, one under normal conditions and one while towing a known added resistance. Since the power output remains the same, any difference in velocity is attributed to the additional resistance.

Swimming efficiency is commonly expressed as the fraction of external mechanical power that is converted into useful propulsive power, known as Froude efficiency (η_F) (Toussaint et al., 1989; Zamparo et al., 2014). To account for the constraints of the aquatic environment, Martin et al. (1981) proposed a theoretical model of swimming propulsion in front crawl from which η_F can be estimated using a speed-based method. This method calculates the ratio between the swimmer's average forward velocity and the average tangential velocity of the hands (v_{hands}), under the assumption that Da and the effective force applied by the hands remain constant at a given steady swimming velocity. Supporting this approach, findings in front crawl (Peterson Silveira et al., 2019, using MAD-System) suggest that the speed-based method yields values of η_F that closely approximate the theoretical maximum (η_F = 1), where energy lost in imparting kinetic energy to the water is considered negligible due to the assumption of constant swimming velocity (Toussaint et al., 1989).

Among swimming techniques, breaststroke stands out due to its distinct mechanical and technical demands. It has been consistently described as the technique with the highest C, as well as a greater frontal area and D_a compared to other techniques (Barbosa et al., 2006; Capelli et al., 1998; Kolmogorov et al., 1997, 2021; Xin-feng et al., 2007). Since drag is directly proportional to projected body surface area (Kjendlie & Stallman, 2008; Pendergast et al., 2005) and a larger frontal area is associated with higher C (Chatard et al., 1985, 1990; Kjendlie et al., 2004a), reducing unnecessary body movements is essential to minimize D_a and C. The breathing action affects a swimmer's streamline and propulsion because the head must move out of the most hydrodynamic swimming position to inhale. In the breaststroke technique, swimmers typically breathe during each cycle, lifting the head and part of the trunk, which might increase frontal surface area and drag. However, according to the World Aquatics rules (2022-2025), swimmers are only required to have part of their head breaking the water's surface during each cycle. This means they do not have to fully lift their heads and torsos out of the water every cycle. By reducing the number of breaths and minimizing unnecessary body movements associated with breathing, swimmers can maintain a more streamlined position, possibly reducing drag and conserving energy.

Vilas-Boas (1993) proposed indices to indirectly approach efficiency in the breaststroke technique. The horizontality index measures the predominance of medio-lateral compared to vertical movements of a limb extremity (i.e., hands or feet) during the propulsive phase of swimming. The antero-posterior stabilization index reflects how stable or "anchored" a limb remains in the forward–backward (antero-posterior) direction while moving vertically or sideways. Finally, the total antero-posterior stabilization index builds on the previous measure by also including medio-lateral movement, offering a more comprehensive picture of limb movement stabilization. Another index of efficiency can be obtained from feet displacement during the propulsive phase, calculated as the difference between the final and initial feet positions. Higher values indicate that the swimmer was able to complete the movement with the feet placed further forward relative to the starting point, suggesting effective stabilization and forward propulsion of the body. In contrast, lower (or negative) values imply that the swimmer primarily pushed the water backward, with limited forward progression of the body. Literature on propulsive efficiency in breaststroke is scarce, highlighting the need to apply existing indices and propose new ones to deepen the understanding of this swimming technique.

The main objectives of this study were fivefold: (i) to assess propulsive efficiency in breaststroke (adapted from existing literature) based on the ratio between the swimmer's center of mass and propulsive segments velocities; (ii) to measure hands, feet and global efficiency throughout the swimming cycle; (iii) to evaluate whether stability indices (adapted from the literature) are meaningful and useful for breaststroke analysis; (iv) to compare two different breathing patterns (every cycle vs. every two cycles) across all studied variables; (v) to examine the relationships between efficiency and stability indices with C and D_a. It was hypothesized that: (i) the newly proposed indices of propulsive efficiency (hands, feet and global) would differ between the two breathing patterns, with higher efficiency values expected when breathing every two cycles due to reduced technical disruption; (ii) breathing every cycle would lead to decreased motor path stabilization due to greater body oscillation; (iii) C and D_a would be higher when breathing every cycle; (iv) associations would be found between global efficiency and energetic variables, with higher efficiency associated with lower C; (v) greater motor path stabilization would be positively related to propulsive efficiency and negatively related to energetic demands.

2. Methods

Participants

Fifteen competitive swimmers participated (nine females), recruited from local teams. Performance level was classified with the World Aquatics Point Scoring using personal bests in the 100 m breaststroke short course pool (25 m). Female and male swimmers were, respectively, 16.7 ± 5.5 vs 15.9 ± 3.0 years old, 49.4 ± 10.1 vs 57.0 ± 11.6 kg of body mass, 158.9 ± 9.2 vs 169.3 ± 10.1 cm of height and 355.7 ± 97.8 vs 376.2 ± 122.6 points. Inclusion criteria were: (i) ≥ five years of competitive swimming experience; (ii) active competition at a regional or higher level; and (iii) absence of injuries in the six months prior to testing. Ethical approval was granted by the institutional review board (CEFADE 36/2022). All procedures complied with the Declaration of Helsinki (2024) and written informed consent was obtained from participants and, when underage, from their legal guardians.

Data collection procedures

Testing was conducted in a 25 m indoor pool. All swimmers completed a standard 1000 m race preparation warm-up. Then, each swimmer performed an incremental intermittent protocol twice, once breathing every cycle and once every two cycles, in randomized order and in different days, to assess energy expenditure. The protocol comprised 5 x 200 m breaststroke bouts with 0.05 $m \cdot s^{-1}$ velocity increments and 30 s rest between steps (adapted from Fernandes et al., 2010; Carvalho et al., 2020; Monteiro et al., 2020). A 48 h interval separated the two testing days. On one day, swimmers rested 30 min after the incremental protocol and performed three maximal 25 m trials in each breathing pattern for kinematic assessment, with 4 min of passive rest between trials to minimize fatigue effects (Toubekis et al., 2011). Performance times were monitored, and trials were repeated if outside ~2.5% of their target race pace. On the other day, swimmers performed two maximal 25 m trials per breathing pattern, one with added resistance and one without, in randomized order, for Da determination.

Energy cost

In the incremental protocol, the final step velocity was individually determined from each swimmer's current 200 m breaststroke personal best, corresponding to ~0.3 $m \cdot s^{-1}$ slower than target pace. Trials began in-water and swimmers followed a visual pacing system (Pacer2Swim; KulzerTEC, Santa Maria da Feira, Portugal) with flashing lights placed along the pool bottom (Fernandes et al., 2012; Zacca et al., 2019). Swimmers were instructed to minimize gliding during starts and turns to maintain steady velocity synchronized with the pacing lights (Gonjo et al., 2021). Breath-by-breath gas exchange was measured using a portable gas analyzer (K5, Cosmed, Rome, Italy) at rest (2 min), during the 30 s intervals between steps and for 5 min after termination.

The device was calibrated before each trial according to manufacturer instructions using ambient air, reference gas concentrations (16% O_2 and 5% CO_2) and a 3 L syringe (Fernandes et al., 2012; Sousa et al., 2014). Immediately after each 200 m step, swimmers exhaled into the mask as soon as it was positioned to minimize delay between exercise cessation and respiratory data collection (Monteiro et al., 2020; Zacca et al., 2022). Capillary blood samples (5 µL) from the fingertip were collected at rest, after each step, and at 1, 3, 5 and/or 7 min post-exercise to determine peak blood lactate concentrations ([La^-]) using a Lactate Pro2 analyser (Arkay, Inc., Kyoto, Japan) (Zacca et al., 2019; Carvalho et al., 2020).

The peak oxygen uptake ($\dot{V}O_2$peak) for each incremental step was estimated by backward extrapolation to time zero of recovery, applying both linear and exponential regressions to the first 20 s of post-exercise data (Lavoie et al., 1983; Monteiro et al., 2020; Zacca et al., 2022). $\dot{\mathrm{E}}_{\mathrm{tot}}$ per step was calculated using the Equation 2, where $\dot{E}_{\mathrm{aer}}$ is the aerobic contribution, $\dot{E}_{\mathrm{an[La]}}$ is the contribution from blood lactate accumulation of La^-, $\dot{E}_{\mathrm{anPCr}}$ is the phosphocreatine contribution, representing the anaerobic alactic contribution. All power contributions were converted to Watts to allow direct comparison across pathways and steps, using standard methods (di Prampero et al., 1974; Capelli et al., 1998; Peterson Silveira et al., 2019).

$$\dot{\mathrm{E}}_{\mathrm{tot}} = \dot{E}_{\mathrm{aer}} + \dot{E}_{\mathrm{an[La]}} + \dot{E}_{\mathrm{anPCr}} \quad (2)$$

C was estimated as the ratio between $\dot{\mathrm{E}}_{\mathrm{tot}}$ and swimming velocity, following established procedures (di Prampero et al., 1974; Fernandes et al., 2005; Figueiredo et al., 2013; Vilas-Boas and Santos, 1994). To examine the relationship between C and velocity, both linear and exponential regression models were tested using data from all swimmers of the incremental protocol and stratified by breathing pattern. The quality of fit was assessed to determine the most appropriate regression form for each condition, ensuring that the model captured the curvilinear or linear trend between energetic demands and velocity. Once the optimal model was identified, extrapolated C values were computed for the swimming velocities recorded during maximal-effort kinematic trials, allowing direct integration of energetics with performance outcomes. This approach enabled a more robust estimation of C at intensities corresponding to real competitive conditions, while accounting for individual and group-level differences in breathing strategies.

Kinematics

Kinematic data were obtained with a dual-media optoelectronic motion capture system (Qualisys AB, Sweden) combining underwater and dry-land recordings. The underwater setup included seven cameras (six Oqus 300+u and one Oqus 700+u), while the dry-land configuration comprised nine cameras (six Oqus 400 and three Oqus 310+). Both subsystems operated synchronously at 100 Hz and were independently calibrated by positioning a static L-frame to define the global coordinate system, followed by a dynamic calibration using a fixed-length wand to establish a calibrated volume of ~2.0 × 5.5 × 1.5 m^3. Then, a twin-calibration procedure was conducted to align both media into a unified global coordinate system, producing a fully integrated 3D dual-media capture volume. The coordinate axes were defined as Y for the swimming direction (horizontal), X for the right medio-lateral direction and Z for upward vertical displacements. Manufacturer's calibration procedures ensured twin-system error < 1.5 mm. The relative position of water surface was established by recording the calibration wand at water level and Z-axis values were considered negative below the water level.

To model swimmers during testing, 50 retroreflective markers were placed on predefined anatomical landmarks according to a modified version of the Qualisys Sports Marker Set (2021), as described in detail before (Alves et al., 2025). Marker trajectories were processed in Qualisys Track Manager (Qualisys AB, Sweden), where data gaps were corrected using polynomial and relational interpolation methods before exporting to Visual3D v5.01.21 (C-Motion, Canada). Trajectories and computed joint angles were low-pass filtered with a fourth-order Butterworth filter with a 6 Hz cut frequency and a six degrees-of-freedom (6DoF) biomechanical model was constructed in Visual3D. A complete swimming cycle was defined from the beginning of the upper limbs' outsweep to its recurrence, with two consecutive cycles within the calibrated volume selected for analysis.

Hand speed-based efficiency was calculated by adapting the Peterson-Silveira et al. (2019) approach to our dataset, following the theoretical framework derived from Alexander's (1977) and Toussaint's (2000) velocity-ratio models and incorporating Martin's (2008) subsequent development, which estimates (rather than directly measures) the required segmental velocities. Unlike Martin et al. (1981) and Peterson-Silveira et al. (2019), our velocities were directly computed from the 6DoF biomechanical model, itself constructed from observed marker positions. The same procedure was applied to the feet trajectory. Global efficiency was calculated combining both hands and feet velocities with the duration of their respective propulsion phases. Hands (v_{hand}), and feet (v_{feet}) mean velocity were defined as the average between their left and right centers of mass velocities, considering only propulsion phases: for the upper limbs, outsweep, insweep and downsweep, and insweep and upsweep; for the lower limbs, outsweep and insweep.

Hand speed-based efficiency ($\eta_{F,\text{hands}}$) was computed as the ratio between the swimmer's center of mass velocity in the swimming direction during upper-limb propulsion phases (v_{CoM,y_hands}) and the magnitude of the hands' velocity (v_{hand}), as shown in Equation 3, (Peterson-Silveira et al., 2019). The same approach was applied to the feet, where v_{CoM,y_feet} represents the swimmer's center of mass velocity in the swimming direction during lower-limb propulsion phases and v_{feet} denotes the feet velocity magnitude (Equation 4). This procedure allowed quantification of the propulsive effectiveness of the hands and feet independently, providing specific indices of segmental efficiency.

$$\eta_{F,hands} = \frac{v_{CoM,y\_hands}}{v_{hands}} \tag{3}$$

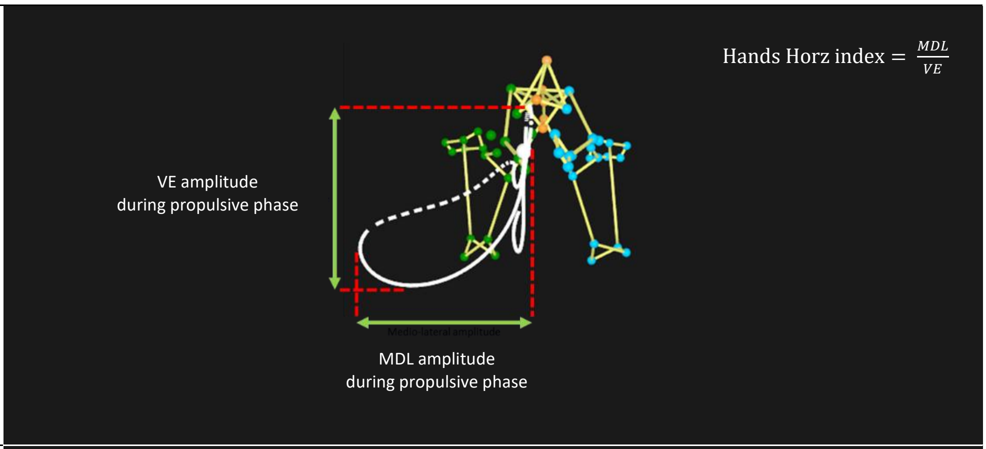
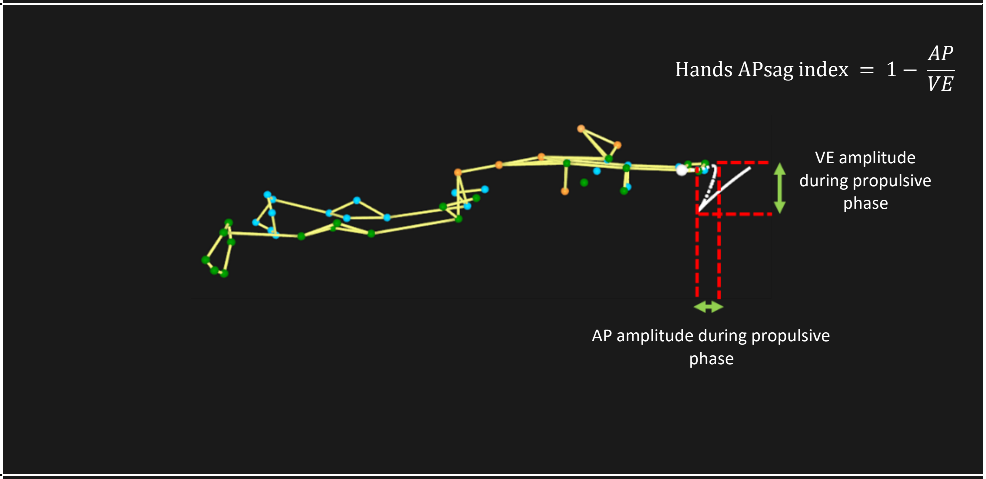
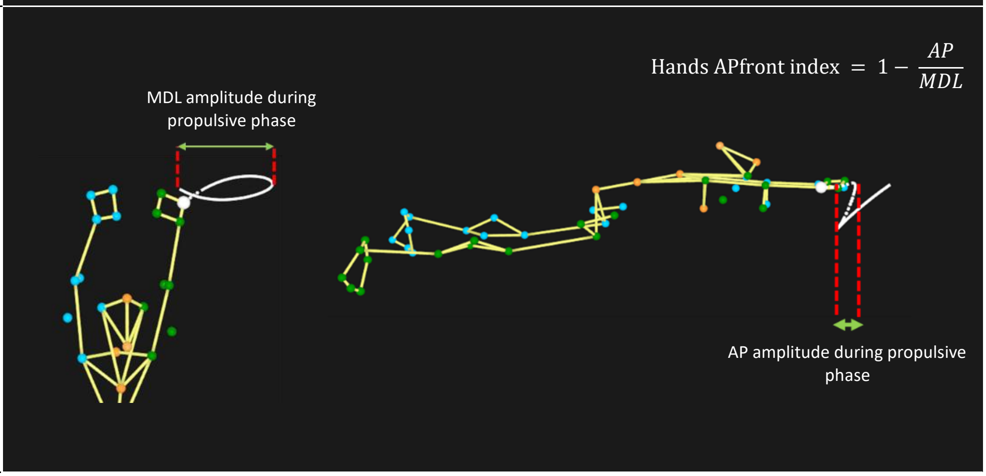
$$\eta_{F,feet} = \frac{v_{CoM,y\_feet}}{v_{feet}} \tag{4}$$

Overall efficiency for one complete breaststroke cycle was estimated using a weighted average that accounted for the duration of each propulsive phase. As expressed in Equation 5, $\eta_{F,global}$ represents the global efficiency, calculated from the efficiencies of the upper and lower limbs weighted by the corresponding propulsion times (t_{hands} and t_{feet}). This approach ensured that the contribution of each segment to total efficiency reflected not only its propulsive effectiveness but also its relative duration within the cycle.

$$\eta_{F,global} = \frac{\eta_{F,hands} \times t_{hands} + \eta_{F,feet} \times t_{feet}}{t_{hands} + t_{fet}} \tag{5}$$

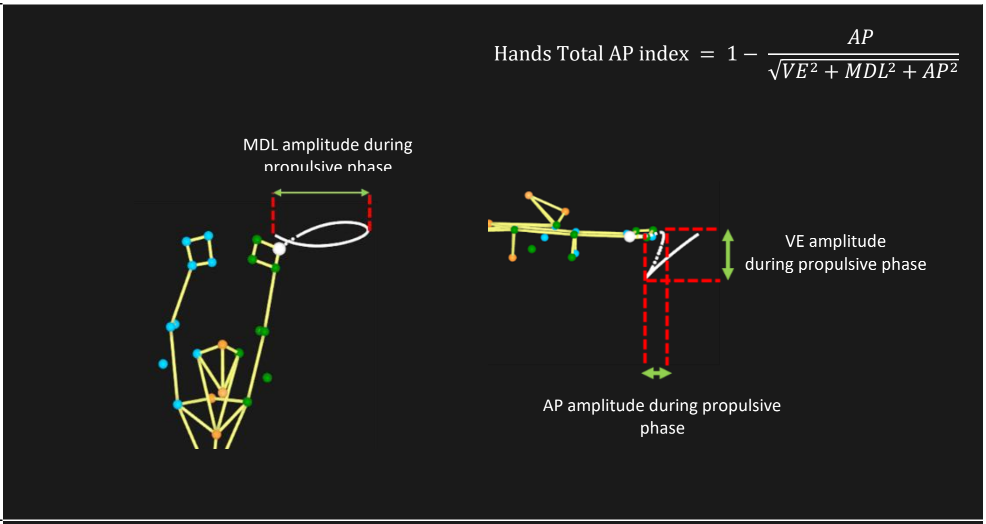
In addition to efficiency measures, complementary kinematical indices were computed as proposed before (Vilas-Boas, 1993), with definitions summarized in Table 2. Among these, the total antero-posterior stabilization index of the hands and feet motor path in the sagittal plane was adapted from the original formulation, which defined it as the ratio between the antero-posterior displacement amplitude and the sum of medio-lateral and vertical amplitudes. However, in the current study, the three amplitude components of the motor path were considered directly to provide a more integrative description of segmental trajectory control. This adaptation allowed assessment of the relative stability of limb trajectories across three dimensions, rather than limiting interpretation to a single plane.

Table 1 - Description and schematic representation of the calculated kinematical indices.

Variables	Schematic presentation
Horizontality index of the hands motor path Ratio between the MDL and the VE amplitudes of hands motor path, during the propulsive phase of one upper limb's cycle.	
Antero-posterior stabilization index of the hands motor path in the sagittal plane Ratio between the VE and the AP amplitudes of hands motor path, subtracted from 1, during the propulsive phase of one upper limb's full cycle.	
Antero-posterior stabilization index of the hands motor path in the frontal plane Ratio between the MDL and the AP amplitudes of hands motor path, subtracted from 1, during the propulsive phase of one upper limb's full cycle.	

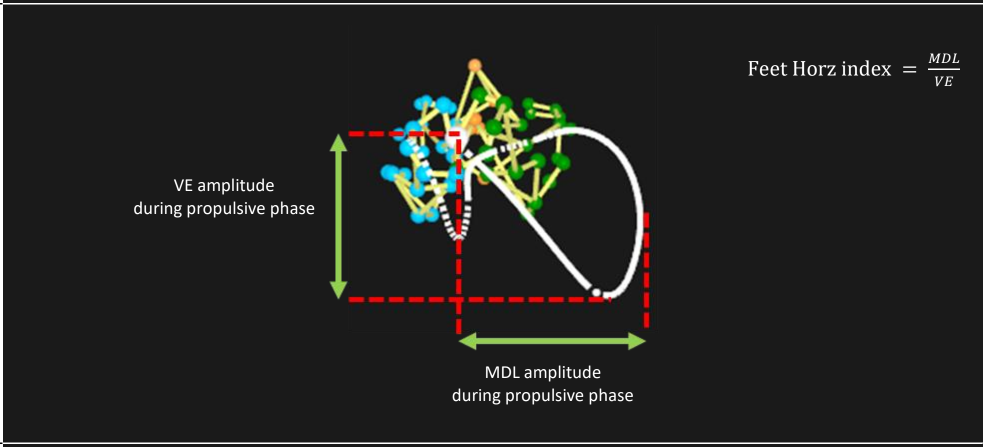
Total antero-posterior stabilization index of the hands motor path in the sagittal plane

Ratio of AP amplitude to the resultant amplitude of the hands motor path, considering AP, VE and MDL components, subtracted from 1, during the propulsive phase of one full upper limbs cycle.



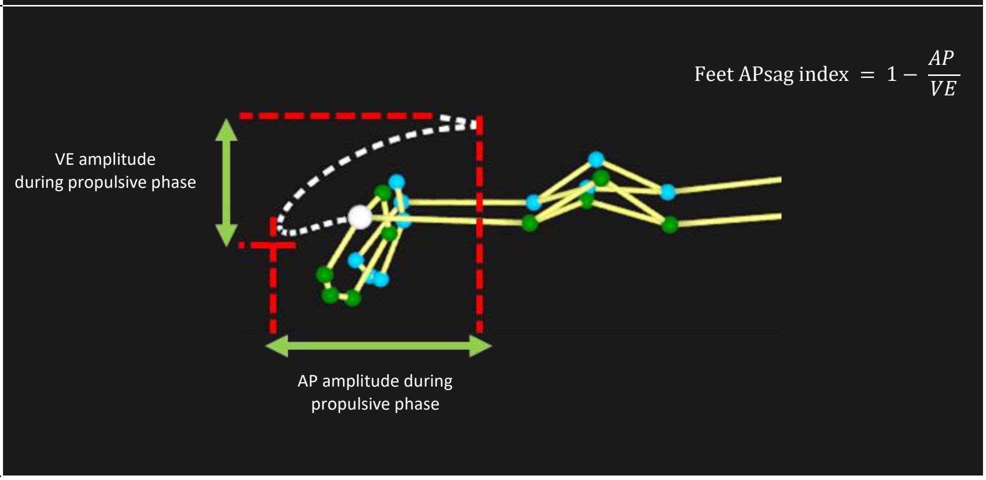
Horizontality index of the feet motor path

Ratio between the MDL and the VE amplitudes of feet motor path, during the propulsive phase of one full lower limbs cycle.



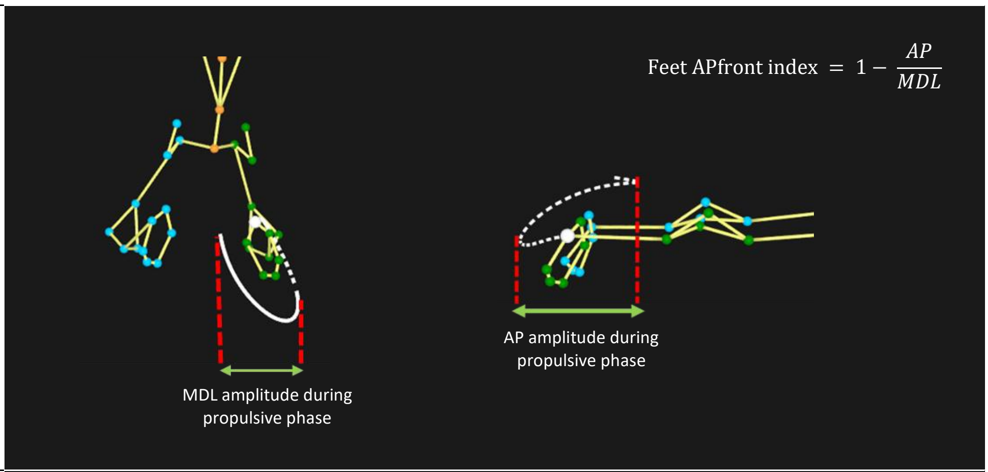
Antero-posterior stabilization index of the feet motor path in the sagittal plane

Ratio between the VE and the AP amplitudes of feet motor path, subtracted from 1, during the propulsive phase of one full lower limbs cycle.



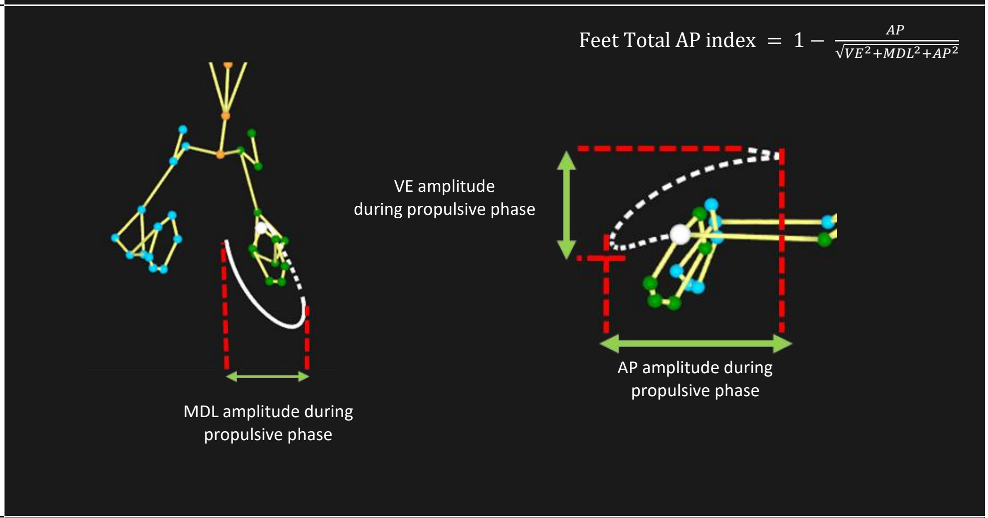
Antero-posterior stabilization index of the feet motor path in the frontal plane

Ratio between the MDL and the AP amplitudes of feet motor path, subtracted from 1, during the propulsive phase of one full lower limbs cycle.



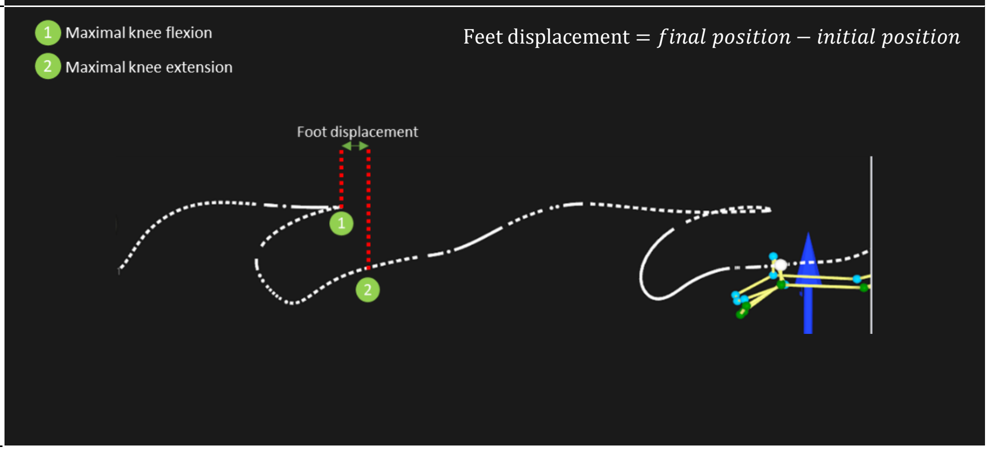
Total antero-posterior stabilization index of the feet motor path in the sagittal plane

Ratio of AP amplitude to the resultant amplitude of the feet motor path, considering AP, VE and MDL components, subtracted from 1, during the propulsive phase of one full lower limbs cycle.



Feet displacement

Calculated as the difference between the final and initial feet positions



Total antero-posterior stabilization index Ratio of the combined AP amplitude of the hands and feet motor paths to the resultant three-dimensional amplitude (AP, VE, and MDL) components) of both limbs, subtracted from 1, during the propulsive phase of a full breaststroke cycle.	$\text{Total AP index} = 1 - \frac{\sqrt{AP_{hands}^2 + AP_{feet}^2}}{\sqrt{AP_{hands}^2 + AP_{feet}^2 + MDL_{hands}^2 + MDL_{feet}^2 + VE_{hands}^2 + VE_{feet}^2}}$

Antero-posterior (AP); vertical (VE); medio lateral (MDL).

Active drag

Active drag was estimated for each breathing pattern using the Velocity Perturbation Method (VPM). Participants completed at least one familiarization trial and a 4 min rest interval was provided between efforts to minimize fatigue effects (Toubekis et al., 2011). Swimming velocity was assessed over a 13 m segment (from the 11-24th m) using manual stopwatches operated by two experienced evaluators, with high inter-rater reliability (ICC = 0.88). Trials were conducted individually to avoid drafting and pacing influences, with swimmers instructed to perform an all-out effort from a push-off start while avoiding underwater pull-outs. D_a was calculated as in Equation 6 (Kolmogorov & Duplishcheva, 1992), where D_a represents active drag, D_b the resistance of the perturbation buoy and v_b and v the swimming velocities with and without the device (respectively).

$$D_a = \frac{D_b \times v_b \times v^2}{v^3 - {v_b}^3} \quad (6)$$

The drag of the perturbation buoy was calculated from the manufacturer's calibration of the buoy drag characteristics at different velocities (Kolmogorov & Duplischeva, 1992). At constant velocity, the swimmer is subjected to hydrodynamic resistance (drag force); which can be expressed by Equation 8 (Toussaint et al., 2004). Using the value of k obtained through the VPM, D_a was extrapolated for the velocities achieved during the maximal-effort trials of the kinematic assessment (Equation 7).

$$D_a = k\, v^2 \tag{7}$$

Relationship between variables

To explore the relationship between efficiency, energy expenditure, and hydrodynamic drag, di Prampero's (1986) equation ($v = \dot{E}_{tot} \times \frac{\eta_d}{D}$) was rearranged to $\frac{\dot{E}_{tot}}{v} = \frac{D_a}{\eta_d}$. In the current study, we replaced the term η_d by our proposed estimate of the global propelling efficiency ($\eta_{F,global}$; Equation 5), allowing us to write Equation 9. Despite in this formulation we replaced η_d by $\eta_{F,global}$, and consequently we are not taking into account the difference in contractile efficiency, heat production, internal work energy dissipation (assumed as very similar between the two breathing techniques), and energy transferred to the mass of water, this rearrangement provided a framework to analyze how energy cost ($\dot{E}_{tot}/v$) relates to mechanical drag (D_a) and efficiency ($\eta_{F,global}$), aligning our variables with the theoretical model proposed by di Prampero and enabling comparison across swimmers and breathing conditions.

$$\frac{\dot{E}_{tot}}{v} \approx \frac{D}{\eta_{F,global}} \tag{8}$$

Statistical analysis

Data were analyzed on SPSS Version 25.0 for Windows (SPSS Inc., Chicago, IL, USA) and Microsoft Excel. The normality of all the selected variables was checked for with the Shapiro–Wilk test. Descriptive statistics were computed as mean and standard deviation, together with 95 % confidence intervals and statistical significance was set at $\alpha = 0.05$. Differences between the two breathing patterns were examined with paired samples *t*-test. Effect sizes were estimated using Cohen's d and interpreted as small, moderate and large (d = 0.2, 0.5 and 0.8) (Cohen, 2013). Partial correlation analysis was conducted to explore associations between all variables while controlling for swimming velocity. Correlation strength was interpreted as negligible, low, moderate, strong and very strong ($r \leq 0.1$, 0.3–0.49, 0.5–0.69, 0.7–0.89 and ≥ 0.9) (Hopkins et al., 2009). To further assess hand, feet and global efficiency throughout swimming, breaststroke cycles were time-normalized to 101 data points and Statistical Parametric Mapping one-way ANOVA was applied using MATLAB R2023b (The MathWorks Inc., Natick, Massachusetts, United States) to compare the two breathing conditions.

6. Results

Overall, both breathing patterns showed similar values across the studied variables (Table 2). Differences were observed in hands efficiency, hands antero-posterior stabilization index in the sagittal and frontal planes, total hands antero-posterior stabilization index, feet antero-posterior stabilization index in the frontal plane, total feet antero-posterior stabilization index and feet displacement. Figure 1 illustrates the feet and hands velocities together with the corresponding CoM velocity and efficiency values for each breathing pattern across one complete propulsive cycle of each extremity. SPM revealed no differences between breathing conditions in the center of mass, feet and hands velocity. Similarly, no differences were observed in feet and hands efficiency between the two breathing patterns (Figure 2).

Table 2 – Comparison of efficiency and kinematic variables between the two breathing patterns, using paired t-tests. The values are expressed as mean ± standard deviation, and [95% confidence interval for the mean].

	Br 1/1	**Br 1/2**	**Mean difference**	***t*-test**	***p***	**Cohen's *d***
C (kJ/m)	0.98 ± 0.30 [0.89; 1.07]	0.99 ± 0.24 [0.92; 1.06]	-0.01	-0.14	0.888	-0.022
$\dot{E}_{tot}$ (kJ/min)	60.60 ± 26.96 [52.54; 68.66]	57.60 ± 20.59 [51.44; 63.75]	3.01	0.66	0.512	0.101
Da (N)	49.54 ± 18.90 [43.89; 55.19]	44.35 ± 18.38 [38.85; 49.84]	5.20	1.38	0.176	0.210
$\eta_{F,hands}$	0.67 ± 0.04 [0.65; 0.68]	0.64 ± 0.04 [0.63; 0.65]	0.02	3.15	0.003*	0.481
$\eta_{F,feet}$	0.54 ± 0.10 [0.51; 0.57]	0.55 ± 0.09 [0.53; 0.58]	-0.01	-0.53	0.600	-0.081
$\eta_{F,global}$	0.63 ± 0.05 [0.61; 0.64]	0.61 ± 0.04 [0.60; 0.62]	0.02	2.02	0.050	0.307
vCoM	1.00 ± 0.16 [0.96; 1.05]	0.96 ± 0.14 [0.92; 1.00]	0.05	1.35	0.185	0.206
Hands Horz index	1.46 ± 0.29 [1.37; 1.55]	1.35 ± 0.36 [1.25; 1.46]	0.11	1.43	0.159	0.218

Hands APsag index	0.57 ± 0.20 [0.51; 0.63]	0.43 ± 0.24 [0.36; 0.50]	0.13	2.29	0.027*	0.349
Hands APfront index	0.02 ± 0.35 [-0.08; 0.13]	0.16 ± 0.37 [0.05; 0.27]	-0.14	-3.05	0.004*	-0.466
Hands Total AP index	0.77 ± 0.09 [0.74; 0.79]	0.69 ± 0.09 [0.66; 0.72]	0.08	3.35	0.002*	0.512
Feet Horz index	0.98 ± 0.26 [0.91; 1.06]	1.09 ± 0.28 [1.01; 1.18]	-0.11	-1.86	0.070	-0.283
Feet APsag index	0.09 ± 0.31 [0.00; 0.19]	0.14 ± 0.32 [0.04; 0.24]	-0.05	-1.08	0.287	-0.164
Feet APfront index	0.71 ± 0.12 [0.67; 0.74]	0.58 ± 0.14 [0.54; 0.62]	0.13	3.68	<0.001 *	0.562
Feet Total AP index	0.47 ± 0.12 [0.44; 0.51]	0.51 ± 0.12 [0.48; 0.55]	-0.04	-2.49	0.017*	-0.380
Feet displacement	-0.13 ± 0.16 [-0.18; -0.08]	-0.07 ± 0.16 [-0.12; -0.03]	-0.06	-2.05	0.046*	-0.313
Total AP index	0.60 ± 0.11 [0.57; 0.64]	0.59 ± 0.10 [0.56; 0.62]	0.01	0.69	0.492	0.11

* $p < 0.05$ (two-tailed); hands efficiency ($\eta_{F,hands}$); feet efficiency ($\eta_{F,feet}$); global efficiency ($\eta_{F,global}$); center of mass velocity (vCoM); hands horizontality index (Hands Horz index); hands antero-posterior stabilization index in the sagittal plane (Hands APsag index); hands antero-posterior stabilization index in the frontal plane (Hands APfront index); hands total antero-posterior stabilization index (Hands Total AP); feet horizontality index (Feet Horz index); feet antero-posterior stabilization index in the sagittal plane (Feet APsag index); feet antero-posterior stabilization index in the frontal plane (Feet APfront index); feet total antero-posterior stabilization index (Feet Total AP index).

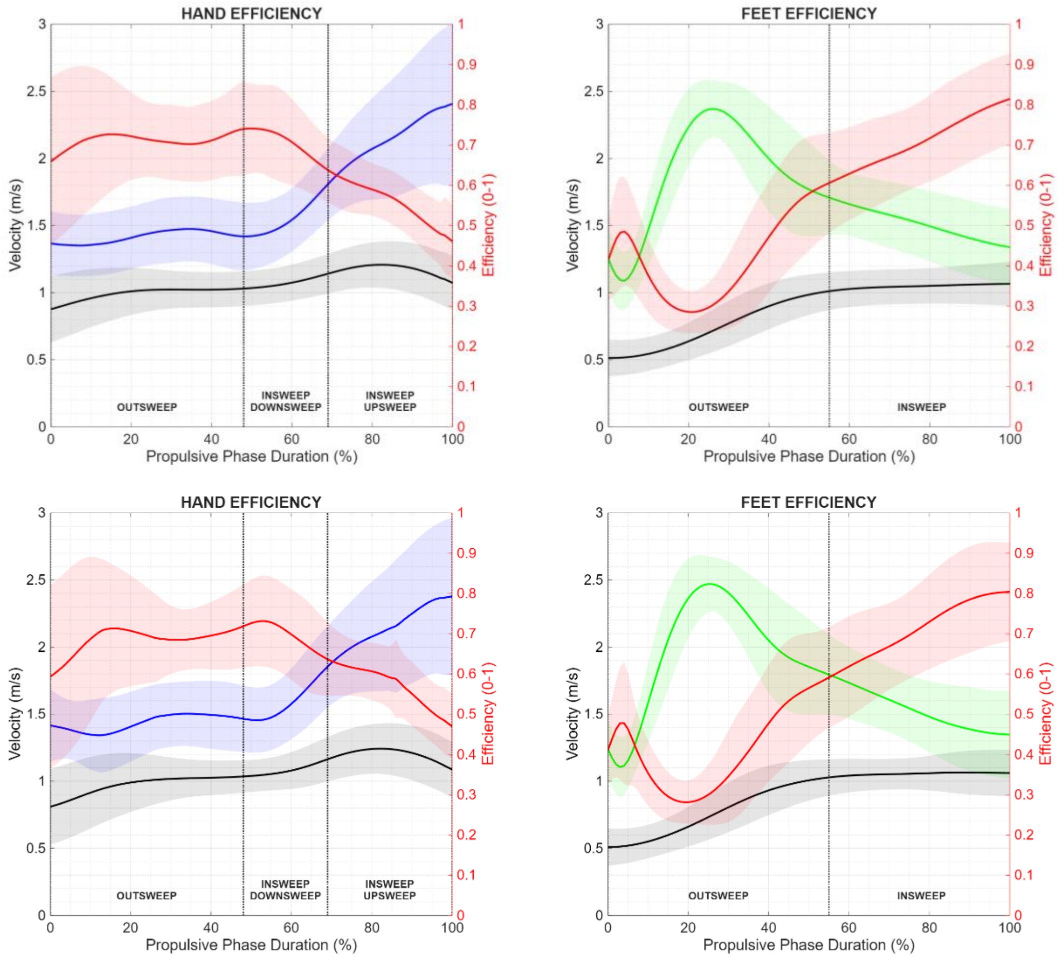


Figure 1 – Hands, feet and CoM velocities (blue, green and black lines, respectively) together with efficiency values (red lines, right side scale) for each breathing pattern (top panels: breathing every cycle; bottom panels: breathing every two cycles).

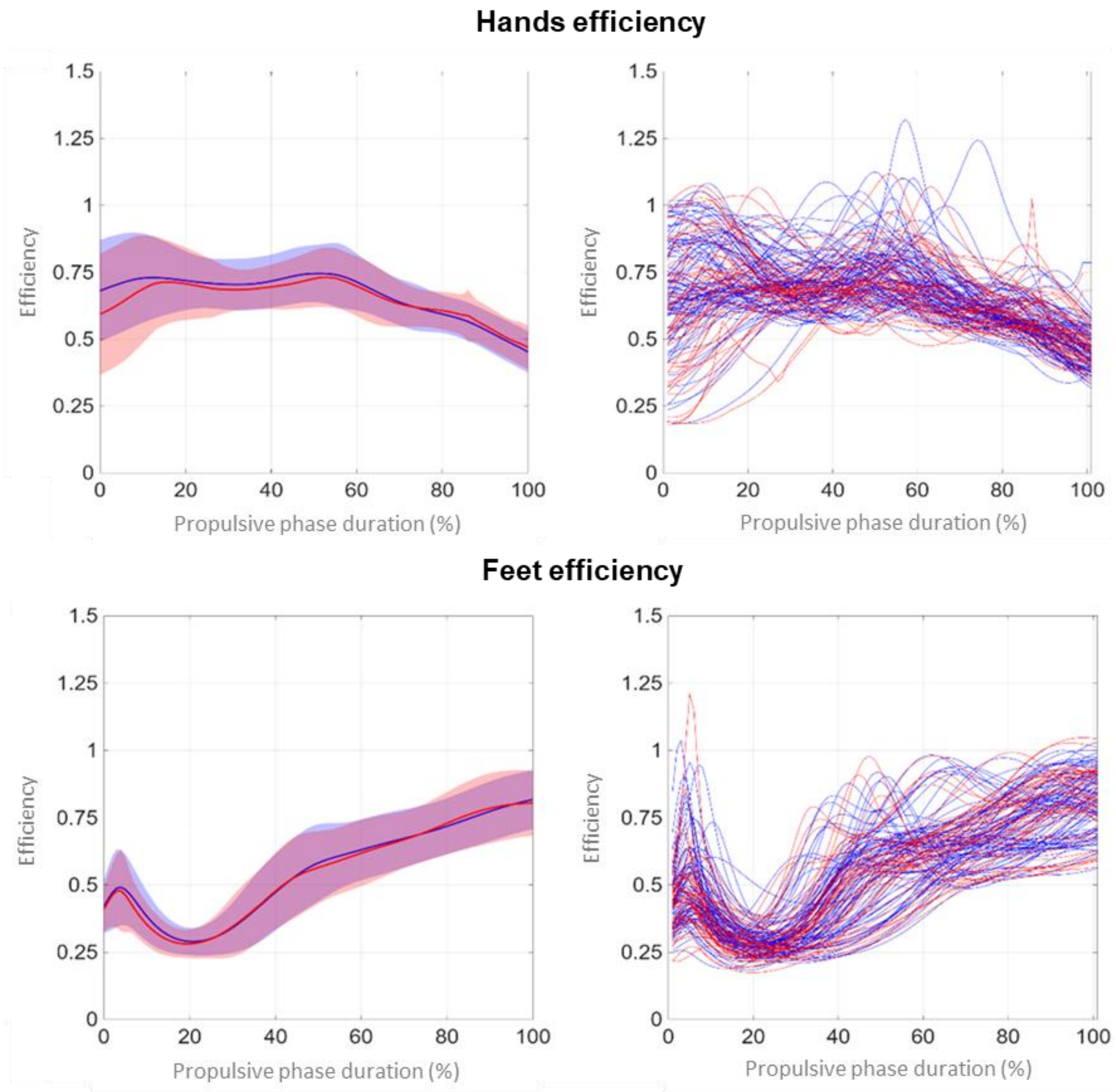


Figure 2 – Hands and feet efficiency along the respective propulsive phase. Left: Group mean curves ± SD and corresponding SPM test results. Right: Overlapping representation of the propulsive phase of all recorded breathing cycles. Red line and shadow: breathing every cycle; blue line and shadow: breathing every two cycles.

Several correlations were observed among the studied variables (Table 3). The total feet antero-posterior stabilization index showed a strong direct relation with feet displacement. C was moderately and inversely associated with the hands antero-posterior stabilization index. $\dot{E}_{tot}$ was moderately and inversely related with the total antero-posterior stabilization index. The total antero-posterior stabilization index displayed a moderate direct relation with hands total antero-posterior stabilization index and a strong direct relation with the feet total antero-posterior stabilization index and with feet displacement. In addition, the feet antero-posterior stabilization index displayed a moderate direct association with feet displacement and a very strong direct relation with total antero-posterior stabilization index.

Figure 3 shows the individual relationships between the ratios of $\dot{E}_{tot}$ to v and of D to $\eta_{F,global}$, across both breathing conditions. The grey line illustrates the theoretical relationship derived from di Prampero's equation using η_d. In contrast, the distribution of experimental data points demonstrates that most values are positioned above or below this theoretical line. This divergence indicates that the observed efficiency patterns do not fully align with the expected mechanical efficiency predicted by the model. Such discrepancies emphasize the influence of interindividual variability (see also Ribeiro et al., 2017) and suggest that practical efficiency values (as the proposed ones, Equations 3–5) may deviate substantially from theoretical assumptions.

Table 3- Partial correlation matrix controlling for v, between variables including both breathing patterns.

	C	$\dot{E}_{tot}$	Da	$\eta_{F.\ hands}$	$\eta_{F.\ feet}$	$\eta_{F.global}$	Hands Horz index	Hands APsag index	Hands APfront index	Hands Total AP index	Feet Horz index	Feet APsag index	Feet APfront index	Feet Total AP index	Feet displacement	Total AP index
C																
$\dot{E}_{tot}$	0.974**															
Da	0.248*	0.292*														
$\eta_{F.\ hands}$	-0.009	-0.032	-0.038													
$\eta_{F.\ feet}$	-0.028	0.009	-0.067	-0.042												
$\eta_{F.global}$	0.009	0.020	-0.019	0.738**	0.611**											
Hands Horz index	0.221*	0.192*	-0.127	-0.113	-0.066	-0.102										
Hands APsag index	-0.518**	-0.498**	0.105	-0.085	-0.134	-0.127	-0.499**									
Hands APfront index	-0.284**	-0.364**	-0.213	0.185	0.288	0.272	0.048*	0.012								
Hands Total AP index	-0.469**	-0.465**	0.058	-0.175*	-0.141	-0.183*	-0.029	0.870**	0.066							
Feet Horz index	-0.001	0.005	-0.157	0.205*	0.434**	0.407**	-0.050	-0.057	0.560**	-0.091						
Feet APsag index	-0.337**	-0.448**	-0.181*	-0.015	-0.029	-0.072	0.126	0.146*	0.759**	0.270**	-0.042					
Feet APfront index	-0.413**	-0.416**	0.030*	-0.189	-0.166	-0.210	0.211	0.724**	0.077	0.956**	-0.113	0.302				
Feet Total AP index	-0.331**	-0.417**	-0.242*	0.046	0.234*	0.135	0.078	0.100	0.931**	0.192*	0.345**	0.905**	0.210*			
Feet displacement	-0.231*	-0.308**	-0.172**	0.001	0.395**	0.241*	-0.072	0.161*	0.780**	0.193*	0.424**	0.686**	0.153*	0.798**		
Total AP index	-0.467**	-0.564**	-0.181*	-0.027	-0.008	-0.046	0.073	0.452**	0.759**	0.588**	0.142	0.897**	0.590**	0.871**	0.713**	

* and ** $p < 0.05$ and 0.01; hands efficiency ($\eta_{F,hands}$); feet efficiency ($\eta_{F,feet}$); global efficiency ($\eta_{F,global}$); center of mass velocity (vCoM); hands horizontality index (Hands Horz index); hands antero-posterior stabilization index in the sagittal plane (Hands APsag index); hands antero-posterior stabilization index in the frontal plane (Hands APfront index); hands total antero-posterior stabilization index (Hands Total AP); feet horizontality index (Feet Horz index); feet antero-posterior stabilization index in the sagittal plane (Feet APsag index); feet antero-posterior stabilization index in the frontal plane (Feet APfront index); feet total antero-posterior stabilization index (Feet Total AP index).

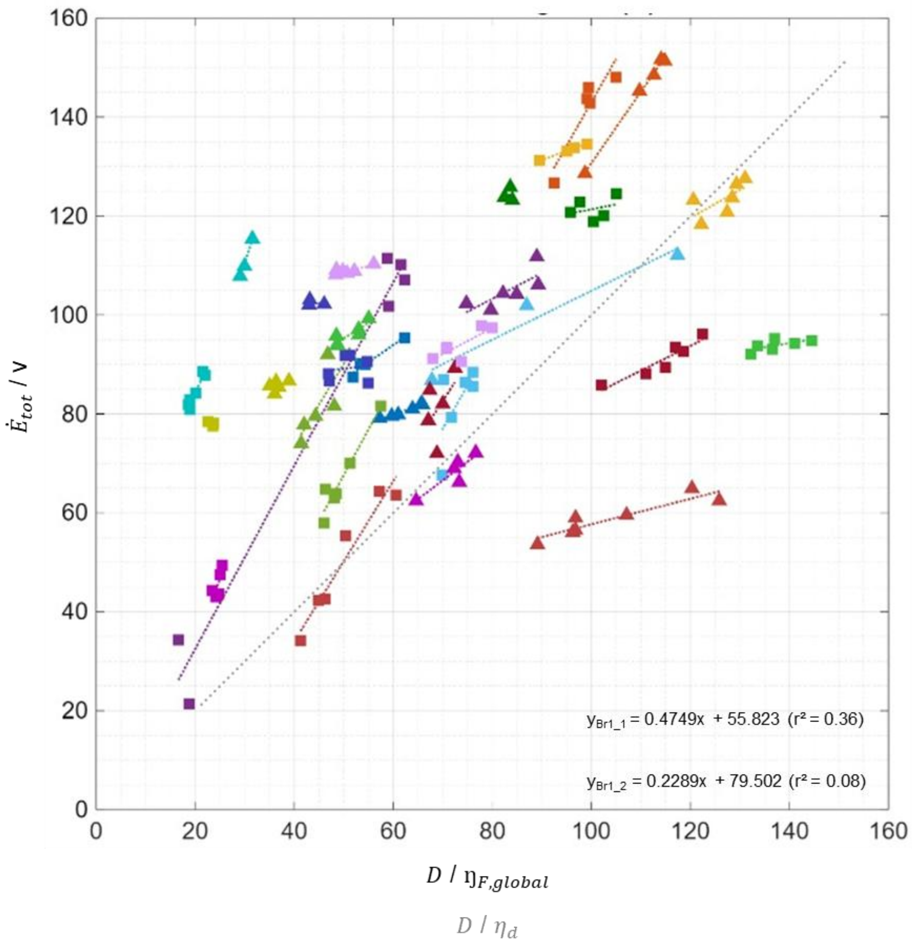


Figure 4 – Individual relationships between the ratios of total energy expenditure ($\dot{E}_{tot}$) to velocity and of hydrodynamic drag (D) to global efficiency ($\eta_{F,global}$), for breathing every cycle and every two cycles (squares and triangles, respectively). Each color denotes a different swimmer. The grey line represents the theoretical relationship between the ratios of $\dot{E}_{tot}$ to v and of D to total mechanical propulsive efficiency (η_d).

7. Discussion

This study aimed to propose new indices of propulsive efficiency in breaststroke and to compare them between two breathing patterns (every cycle vs. every two cycles). Additional analyses included motor path indices of the hands and feet that may be related to swimming efficiency, energy cost and active drag, as well as correlations among all variables. The results partially supported the initial hypotheses. While both breathing patterns produced similar values for most variables, some notable differences emerged. Breathing every cycle was associated with higher hands efficiency, hands antero-posterior stabilization index in the sagittal plane, feet antero-posterior stabilization index in the frontal plane and total hands antero-posterior stabilization index. Conversely, breathing every two cycles yielded higher values for the hands antero-posterior stabilization index in the frontal plane, total feet antero-posterior stabilization index and feet displacement. C showed a moderate inverse relation with the hands antero-posterior stabilization index in the sagittal plane, whereas $\dot{E}_{tot}$ evidenced a moderate inverse association with the total antero-posterior stabilization index, suggesting that greater stabilization of motor paths is linked to reduced C. In addition, the total feet antero-posterior stabilization index exhibited a strong direct relation with feet displacement and both feet antero-posterior stabilization index in the sagittal plane and the antero-posterior stabilization index demonstrated a moderate positive correlation with feet displacement.

Our findings indicated minimal differences between the two breathing patterns studied. Breathing every cycle resulted in greater hands efficiency, hands antero-posterior stabilization index in the sagittal plane and total hands antero-posterior stabilization index, suggesting that avoiding breathing may slightly impair the hands' motor path. This effect could be due to the additional head and trunk movements required for breathing, which may contribute to maintaining cycles rhythm and coordination, thereby enhancing upper limbs propulsion rather than causing disruption, particularly during the insweep phase. Although it is often hypothesized that reducing breathing frequency minimizes technical disruption and improves efficiency in front crawl (e.g., Psycharakis & McCabe, 2011), our results suggest that in breaststroke the standard breathing every cycle pattern may be advantageous for hands propulsion.

Conversely, breathing every two cycles was associated with higher values for the total feet antero-posterior stabilization index and feet displacement. These findings suggest that, while not breathing every cycle might slightly reduce upper limb propulsion, it could simultaneously enhance propulsion generated by the lower limbs. One possible explanation is that omitting a breath allows swimmers to maintain a more streamlined head and trunk position during certain phases of the cycle, potentially favoring lower limbs action effectiveness. However, despite these differences in motor path stabilization, no variation in swimming velocity was observed between the two breathing patterns, which indicates that the compensatory effects of hands and feet may balance each other out at the whole-body level.

The restricted analysis of only two breathing strategies may have limited the scope of the present results, as alternative breathing strategies or individualized approaches could yield different effects. Therefore, future studies including a broader range of breathing strategies and larger samples could provide additional insight into the mechanisms by which breathing modulates breaststroke efficiency and interlimb coordination.

Upper limbs action efficiency has been extensively described and quantified in front crawl (Peterson Silveira et al., 2019; Toussaint et al., 1988; Zamparo et al., 2005), but similar analyses are scarce for breaststroke. Evidence from front crawl (Peterson Silveira et al., 2019) indicates that the speed-based method produces η_F values close to the theoretical maximum (η_F = 1). In the current study, we adapted the same speed-based approach to breaststroke, extending the analysis to both hands and feet efficiency. Unlike front crawl, where the upper limbs provide most of the propulsion (Morouço et al., 2015), propulsion in breaststroke relies primarily on the lower limbs (Mason et al., 1989; Kippenhan, 2002; Shahbazi-Moghadam, 2008). Therefore, assessing feet efficiency alongside hands efficiency is paramount for a complete understanding of propulsive effectiveness in this technique. By combining both measures, we further estimated global efficiency, providing a more comprehensive assessment of propulsion in breaststroke. The current values for hands efficiency ranged between 0.64-0.67, which are consistent with results for front crawl obtained using the same method (~0.62; Peterson Silveira et al., 2019) and higher than those reported when applying a different method (~0.50; Zamparo et al., 2005).

During the breaststroke propulsive cycle, and for a given subject, efficiency values occasionally exceeded unity, indicating that, at those moments, the subject’s CoM velocity was higher than the velocity of the hands or feet. This was more evident in the hands, likely because they were still benefiting from the forward momentum generated by the preceding propulsion of the lower limbs. In contrast, the propulsion phase of the feet begins after the recovery phases of both the upper and lower limbs, meaning it starts from the minimum velocity observed during the cycle (Maglischo, 1993). As a result, the CoM velocity is also lower during this phase, leading to reduced efficiency values. Additionally, the efficiency curve for the hands tends to decrease during the insweep phase of their motor path. This may occur because this phase involves greater body inclination which may lead to higher drag, and in turn reduces CoM velocity and consequently lowers efficiency. Conversely, in the insweep phase of the feet motor path, efficiency tends to increase. This is likely due to the substantially greater force produced by the lower limbs compared to the upper limbs (Maglischo, 1993), resulting in a significant acceleration of the CoM. It is important to note that these indices should not be interpreted as absolute measures of efficiency, since in some instances the values may exceed the unit, a result that is not theoretically consistent with the strict definition of efficiency and the laws of thermodynamics. Indeed, we are using only simple markers of efficiency (Equations 3 – 5), easier to implement in the swimming pool for more applied purposes.

Regarding $\eta_{F.global}$ and its relationship with $\dot{E}_{tot}$, Da and v, the regression analyses yielded low coefficients of determination (r^2 = 0.08 and 0.36 for breathing every two cycles and every cycle, respectively), indicating weak associations between these variables for the global sample. Theoretically, Froude efficiency is defined as the ratio between the power used to overcome drag ($\dot{W}_d$) and the total external power output ($\dot{W}_{ext}$), where power is the product of force and velocity ($\dot{W} = F \times v$). In the current study, $\eta_{F.global}$ was calculated as the ratio between the velocity of the propulsive segments and that of the swimmer's center of mass, without considering the underlying forces, namely the hydrodynamic drag and the total external propulsive forces. Since these forces are not equivalent and cannot be mathematically canceled in the theoretical efficiency equation, this simplification restricts direct comparability with true mechanical (Froude) efficiency. Consequently, this speed-based approach may not fully reflect the mechanical basis of Froude efficiency, which may help to explain the weak correlations values observed (see also Komar et al., 2012).

However, it is important to note that these relationships might be strongly dependent on the individual characteristics of the participants, meaning that the absence of relationships at the overall sample does not imply that significant individual relationships are absent. Interestingly, the slopes of the individual regression lines were similar across swimmers, suggesting consistent patterns despite variability (as observed by Komar et al., 2012 and Mezencio et al., 2020). This inter-individual variability may help to explain the deviations observed from the line of identity in Figure 3, which represents the theoretical relationship derived from di Prampero's equation using total mechanical efficiency. Points above the line of identity indicate relatively lower values of $D_a/\eta_{F,global}$ compared to D/η_d. Given that D remains constant, this implies that $\eta_{F,global}$ is relatively higher than η_d, implying that the former does not account for all energy losses through heat or internal work. Conversely, points below the line of identity indicate the opposite pattern, with relatively higher energy dissipation. Only one swimmer followed the latter pattern for both breaststroke breathing variants, and another displayed it only when breathing every cycle. Since points above the identity line are thermodynamically coherent, these results suggest that our approach to η_F may be theoretically valid. It is also noteworthy that most of the swimmers and conditions presented slopes close to one, either slightly higher or lower, indicating that C and the ratio $D/\eta_{F,global}$ tend to be proportional to the ratio D/η_d. This further reinforces the assumption that the energy dissipated as heat, the internal work and the energy lost to change the water's mechanical energy are similar and comparable across participants and conditions. Nevertheless, perceptible differences remain and warrant further investigation.

In our study, we applied the indices originally proposed by Vilas-Boas (1993) to indirectly assess movement efficiency in the breaststroke technique. We adapted the antero-posterior stabilization index in the sagittal and frontal plane by inverting the ratio, calculating the proportion of antero-posterior amplitude relative to vertical or medio-lateral amplitude, while maintaining the original rationale of evaluating how 'anchored' a limb remains in the forward–backward direction during vertical or medio-lateral motion. This inversion allowed us to align higher index values with greater stabilization, thereby improving interpretability. Additionally, we introduced a modified total antero-posterior stabilization index based on the resultant motor path amplitude, where higher values indicate greater stabilization (contrasting with the original interpretation). The overall aim of these indices was to infer whether swimmers primarily relied on propulsive drag, imposing more antero-posterior oriented propulsive actions (Counsilman, 1968; Hay, 1986; Maglischo, 1982) or whether they depended more on lift-based propulsion, which involves more pronounced oblique and transverse limb movements (Counsilman, 1971; Schleihauf, 1976, 1979).

Vilas-Boas (1993) reported hands motor path horizontality index values ranging from 1.34-1.54 and our results were similar, ranging from 1.35-1.46. Values above one indicate that hands trajectories were predominantly medio-lateral. In contrast, feet horizontality indices ranged from 0.87-0.91, reflecting a more vertical motion. These patterns were further supported by the antero-posterior stabilization indices, which showed higher values for the hands and lower values for the feet, except for the antero-posterior stabilization index in the frontal plane. Analysis of the total stabilization indices of the hands and feet revealed the same pattern, with the hands motor path exhibiting greater stabilization than the feet motor path. This reinforces the distinction between the predominantly antero-posterior and medio-lateral actions of the hands and the primarily vertical motions of the feet. Moreover, these stabilization indices, particularly the hands and feet antero-posterior stabilization index in the sagittal and frontal planes, together with the total antero-posterior stabilization index, showed inverse relations with C and $\dot{E}_{tot}$, indicating that greater stabilization of the propulsive limbs is associated with lower energy demands during breaststroke (as seen before for front crawl by Figueiredo et al., 2012; Mezencio et al., 2020).

The final propulsive index we calculated was feet displacement, with higher values indicating that the swimmer was able to complete the movement with the feet positioned further forward relative to the starting point, suggesting effective stabilization and forward propulsion of the body. Our mean results ranged from -0.13 to -0.07, indicating that while the swimmer's center of mass continued to progress, the feet finished the propulsive phase relatively close to their initial starting position. Notably, feet displacement demonstrated a strong direct relation with the total feet antero-posterior stabilization index, a moderate association with the feet antero-posterior stabilization index in the sagittal plane and a moderate direct relation with total antero-posterior stabilization index. These findings underscore its value as an indicator of propulsive effectiveness. Furthermore, this index can be easily applied in day-to-day training, allowing coaches to visually assess the feet motor path, determining whether the feet move forward, remain close to the initial position or move only backward, which would indicate an ineffective lower limbs action.

8. Limitations and future research

This study has some limitations that should be considered. The relatively small and heterogeneous sample may restrict the generalizability of the findings. Moreover, the experimental design was constrained to only two breathing patterns, excluding more flexible strategies such as breathing every three cycles or adapting breathing according to individual needs. Another limitation concerns the indices employed, which require further validation across diverse swimmer populations and swimming velocities. Although theoretically straightforward to establish, these indices still demand stronger empirical support before broader application. Future research should therefore examine the causal relationships between motor path stabilization, propulsive efficiency and energy cost through longitudinal or intervention-based approaches. Such designs would provide more robust evidence on how technical adjustments influence efficiency and energetics in breaststroke performance.

9. Conclusions

The current study introduced new indices of propulsive efficiency for breaststroke swimming, including hand, feet and global measures, and compared these between two breathing patterns (breathing every cycle versus every two cycles). In addition, it was the first study to analyze efficiency continuously throughout a complete breaststroke cycle. While most variables did not differ between conditions, breathing every cycle enhanced hands' efficiency and stabilization measures, whereas breathing every two cycles improved feet stabilization and displacement. The observed correlation values indicate that greater motor path stabilization is associated with lower energy cost and that feet and total stabilization indices were strongly related to feet displacement. Although global relations between efficiency, energy expenditure and drag were weak, the individual analyses revealed consistent relationships, with similar slopes across swimmers. These findings suggest parallel increases of energy cost with the ratio of hydrodynamic drag to global efficiency, highlighting the relevance of considering both individual and global perspectives when evaluating breaststroke performance.

Chapter 7. General discussion

The primary objective of this doctoral thesis was to compare and characterize two distinct breathing patterns - breathing every cycle and breathing every two cycles - in the breaststroke technique. Specifically, the research aimed to: (1) analyze and compare these breathing patterns through kinematic parameters of key reference points (hand, foot, head, and center of mass) across different movement planes, and (2) evaluate their effects on energy cost, stroke efficiency, and active drag. The central hypothesis posited that reducing breathing frequency would lead to lower energy cost, decreased active drag, and enhanced swimming performance. However, energy cost, active drag, and performance did not show consistent improvements across the total sample. Individual variability was a key factor, with some swimmers performing more efficiently using the reduced breathing pattern, while others benefited from the traditional every-cycle breathing.

The systematic review presented in **Chapter 2** included a total of 73 studies focused on the breaststroke technique. Of these, 26 investigated stroke kinematics, 18 examined coordination parameters, five explored hydrodynamic drag, and 12 analyzed energetic variables. Additionally, nine studies assessed both energetics and kinematics, two addressed both coordination and energetics, and one study investigated both drag and energetics. This distribution highlights that while kinematics is the most frequently studied aspect of breaststroke, research on energetics is comparatively limited, studies on hydrodynamic drag are even scarcer, and investigations that integrate multiple domains remain particularly uncommon.

This gap in literature retrieved from **Chapter 2** provided the rationale for the experimental study described in **Chapter 3**, where we compared C and associated bioenergetic variables between two breaststroke breathing patterns, every cycle vs. every two cycles, across a range of intensities. Additionally, $\dot{E}_{tot}$ was extrapolated to sprint paces (50 and 100 m) to assess potential performance implications of each breathing pattern. Breathing every two cycles resulted in higher values of C and $\dot{E}_{tot}$ at step 2, during the incremental protocol (5 x 200 m), compared to breathing every cycle. Additionally, this restricted breathing pattern elicited higher [La$^-$] at steps 3 and 4. Greater $\dot{V}O_2$ peak values were also observed at steps 1 and 2, along with elevated respiratory quotient scores at steps 2 and 3. After controlling for World Aquatics points, breathing every two cycles resulted in higher $\dot{E}_{tot}$ values at steps 1, 2, and 5.

Although breaststroke is generally associated with lower $[La^-]$ concentrations and slower velocities at the anaerobic threshold compared to other swimming techniques (Carvalho et al., 2020; Di Prampero et al., 2008; Holfelder et al., 2013; Marinho et al., 2011), key ventilatory and metabolic variables, such as $\dot{V}O_2max$, appear to be similar between breaststroke and front crawl (Lomax et al., 2022). Previous studies on breathing pattern effects have primarily focused on front crawl, with mixed results. Some found no differences in post-exercise $[La^-]$ between normal and controlled-frequency breathing (Kapus et al., 2003; Key et al., 2014; Murlasits et al., 2023; West et al., 2005), while others observed lower $[La^-]$ under controlled breathing conditions (Hölmer & Gullstrand, 1980). Additionally, controlled-frequency breathing has been linked to reduced heart rate and ventilatory responses (West et al., 2005; Key et al., 2014).

In **Chapter 3**, higher $\dot{V}O_2$ peak and $[La^-]$ values were observed with the reduced breathing pattern. This contrasts with findings by Zompanakis et al. (2021), who reported greater $[La^-]$ concentrations when swimmers breathed every cycle compared to every three cycles during a 25 m breaststroke effort. These discrepancies may reflect differences in testing protocols, swim distances, or swimmers' characteristics. Reduced oxygen availability under hypoxic conditions has been shown to shift energy production from aerobic metabolism to glycolysis, thereby increasing $[La^-]$ accumulation to meet ATP demands (Kierans & Taylor, 2021). This mechanism may help explain the elevated $[La^-]$ values observed when swimmers breathed every two cycles. Conversely, elevated carbon dioxide levels during exercise may inhibit $[La^-]$ accumulation (West et al., 2005; Hölmer & Gullstrand, 1980), potentially leading to lower lactate concentrations.

As shown in **Chapter 2**, previous research has presented that increases in breaststroke velocity are accompanied by higher segmental velocities, modifications in arm-leg coordination, and alterations in stroke phase durations (Leblanc et al., 2007; Oxford et al., 2017; Takagi et al., 2004). As swimming v rises, greater upper and lower limb propulsion and shorter glide phases have been consistently reported (Chollet et al., 2004; Seifert & Chollet, 2005; Fernandes et al., 2024). These coordination adjustments likely contribute to the higher $\dot{E}_{tot}$ values observed at faster velocities, a relationship also described for front crawl by Figueiredo et al. (2013) and Zacca et al. (2022). Although swimmers adopt distinct coordination patterns across the 50, 100, and 200 m breaststroke events, in **Chapter 3**, $\dot{E}_{tot}$ values were extrapolated for a velocity range between 1.4 and 2.0 $m \cdot s^{-1}$ to better understand their potential implications across sprint and middle-distance events.

While the r^2 values for both exponential and linear regressions were similar across the tested breaststroke breathing patterns, the exponential model produced notably higher predicted values. These exceeded those reported in the literature, especially considering that no existing data currently support $\dot{E}_{tot}$ values for breaststroke at velocities above 1.6 $m \cdot s^{-1}$. Therefore, the linear regression appears to be the best-fit model, consistently with previous findings reporting that breaststroke C and $\dot{E}_{tot}$ increase linearly across a range of velocities (Capelli et al., 1998; Vilas-Boas & Santos, 1994). While theoretical models propose that energy output should scale with the cube of velocity, the observed linear relationship can be attributed to variations in coordination and overall efficiency across different velocities (Vilas-Boas & Santos, 1994). This discrepancy might result from a relatively more pronounced efficiency increase compared to drag as swimming velocity rises (Vilas-Boas & Santos, 1994). In addition, the substantial energy expenditure required to accelerate the body during the push phase likely contributes to this pattern, compensating for the velocity loss during the non-propulsive phase of the cycle (Capelli et al., 1998; Fernandes et al., 2024).

Individual swimmers exhibit unique characteristics, resulting in highly individualized responses (Fernandes et al., 2005; Dadashi et al., 2013; Fernandes et al., 2024). Therefore, in **Chapter 3**, an individual-level analysis was conducted to address sample variability, which may have contributed to the lack of statistically significant differences in the group-level analysis. Some swimmers showed increased energy demands ($\dot{E}_{tot}$) when breathing every two cycles, particularly at lower velocities, while others exhibited higher $\dot{E}_{tot}$ when breathing every cycle at faster velocities. The strength of the relationship between velocity and energy demand varied among swimmers, with some demonstrating consistent patterns (high r^2) and others showing more variability (lower r^2). Certain swimmers adapted equally well to both breathing patterns, whereas others clearly favored one, suggesting that efficiency depends on individual physiology and technique. Overall, the choice of breathing pattern involves a trade-off: breathing every cycle may increase oxygen availability but also hydrodynamic drag, while breathing every two cycles enhances the streamline position at the potential cost of limited oxygen supply, especially at higher intensities.

Breathing every two cycles presented higher $\dot{V}O_2$ peak and [La^-] values compared to the traditional breathing every cycle in **Chapter 3**. Consequently, it was important to investigate which variables could explain these differences. Since hydrodynamics may provide a plausible explanation, this was the focus of **Chapter 4**, where the impact of two breathing patterns on swimmers' hydrodynamic characteristics was examined. It was hypothesized that breathing every two cycles would reduce D_a compared to breathing every cycle. However, the main findings revealed no differences in hydrodynamic variables, v_{free}, v_{tow}, D_a, C_{Da} and P_{to}, between the two breathing conditions, even after adjusting for age and swimming velocity.

The VPM method was chosen for this study because it allows for D_a assessment specifically in breaststroke, making it one of the few suitable tools for evaluating hydrodynamic resistance in this technique. 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 below 5.4% for key hydrodynamic parameters. The study also found no differences in maximal power output between trials with and without the added buoy, indicating that the method is robust despite potential variability in swimmers' effort. Although individual power variability was not directly assessed, the low error supports the method's reliability. A noted limitation is its reliance on a single maximal trial; however, additional trials could induce fatigue, undermining the assumption of consistent maximal power.

Other experimental approaches have been proposed to measure D_a, primarily in front crawl. However, results across these methods remain inconsistent. For example, the Measuring Active Drag (MAD) system (Hollander et al., 1986), which is limited to front crawl, and the Assisted Towing Method (ATM) at constant speed (Alcock & Mason, 2007) typically yield higher mean D_a values than the VPM (Mason et al., 2013; Toussaint et al., 2004). In contrast, the Naval Architecture Based Approach has shown comparable results to the VPM at maximal velocities (Webb et al., 2011). Notably, for the same mean maximum velocity, the MAD and ATM methods produced results that differed by as much as 55%, with ATM producing higher values (Formosa et al., 2012). Such discrepancies likely stem from variations in swimmer technique and posture during testing, as well as differences in the theoretical assumptions underlying each method's estimation of hydrodynamic resistance (Sacilotto et al., 2023).

The individual analysis revealed a similar trend to that observed in **Chapter 3**, showing that some swimmers benefit from breathing every cycle, while others exhibit more favorable performance variables when breathing every two cycles. A notable portion of the swimmers (40%) experienced a reduction in D_a when breathing every two cycles compared to every cycle, with some also achieving higher velocities. This suggests that, for certain individuals, less frequent breathing may enhance hydrodynamic performance in breaststroke. By reducing breathing frequency, these swimmers may maintain a better streamlined position and minimize the frontal drag, thereby lowering D_a and improving velocity. These findings align with previous research in front crawl, where not breathing during a 25 m trial resulted in faster times, higher velocities, and increased stroke frequency compared to more frequent breathing patterns (Couto et al., 2015; Pedersen & Kjendlie, 2006).

Conversely, an opposite trend was observed in some swimmers, where breathing every cycle resulted in better hydrodynamic performance. These individuals exhibited lower D_a values with the "normal" breathing pattern, and six of them also achieved higher velocities compared to when breathing every two cycles. One possible explanation is that these swimmers have developed a refined technique that minimizes disruptions to their streamlined position while breathing. For example, they may perform the breathing motion with reduced torso extension, thereby limiting the increase in frontal surface area and minimizing drag. Given that drag is influenced by velocity, body shape, and frontal area (Kjendlie & Stallman, 2008), this ability to maintain a more hydrodynamic position during inhalation may allow them to sustain lower D_a values and achieve higher velocities, even when breathing every cycle.

Comparison of the pooled data using paired t-tests revealed no significant differences in D_a, C_{Da} and, P_{tot} between the two breathing patterns. This absence of differences may be attributed to swimmers not substantially raising their torso when breathing every cycle, or to the possibility that torso elevation remains consistent regardless of breathing frequency. These findings highlight the need for a detailed kinematic analysis to identify subtle technique-related variations that may not be captured through hydrodynamic measures alone. FD is a non-linear measure that quantifies the complexity of a movement time series, with higher values indicating greater variability and intricacy in motor control, and dv quantifies the fluctuations in a swimmer's speed within a single stroke cycle, reflecting the interplay of propulsion and drag forces throughout the movement. For this reason, **Chapter 5** focused on a comprehensive kinematic comparison between two breaststroke breathing patterns, specifically analyzing and comparing kinematics, dv and FD between these two breathing conditions.

In **Chapter 5**, we divided the analysis of breaststroke cycles based on breathing patterns. In the breathing every cycle pattern, each cycle included a breath. In the breathing every two cycles pattern, each pair of cycles includes one non-breathing cycle followed by a breathing cycle, which we specifically refer to as the breathing cycle following a non-breathing cycle to avoid any confusion with the consecutive breathing cycles. Therefore, this distinction led to the study of three types of cycles: (i) the breathing cycle, (ii) the non-breathing cycle, and (iii) the breathing cycle following a non-breathing cycle. We hypothesized that the not breathing cycle would induce measurable kinematic changes compared to the breathing cycle, and that reducing breathing frequency would lead to lower dv and FD values, reflecting enhanced efficiency and motor control stability. Differences between the three breaststroke swimming cycles were minimal and not clearly pointing to the superiority of one of the breathing techniques.

The breathing cycle and the breathing cycle following a non-breathing cycle exhibited higher minimum and lower maximum head depths compared to the non-breathing cycle. While the non-breathing cycle presented head positions closest to the surface when above water, it also showed the deepest submersion. This was expected, as swimmers did not lift their heads to breathe. However, the data suggest that not breathing may lead to greater head sinking during the cycle. Additionally, the non-breathing cycle showed the lowest vertical and horizontal head amplitudes above water, consistent with swimmers minimally breaking the surface to comply with World Aquatics rules, which require the head to emerge during each cycle, though breathing itself is not mandatory.

When swimmers breathe, the head rises above the water surface, potentially increasing vertical displacement and the cross-sectional frontal area, which may elevate hydrodynamic drag (Kjendlie & Stallman, 2008). This less streamlined position can also lead to a higher C (Chatard et al., 1985, 1990; Kjendlie et al., 2004a, b). In contrast, during non-breathing cycles, the head remains closer to the surface for longer, reducing vertical movement. However, in our study, thorax angle did not differ between the three cycle types, and no differences in active drag were observed between breathing patterns during 13 m maximal bouts (Alves et al., 2024). This could reflect a technical evolution in breaststroke, which has become flatter over the past decades. Earlier studies reported more pronounced thorax angles (53°– 63°) associated with undulating styles (Persyn et al., 1992, 2005; Sanders, 1996; Vilas-Boas & Santos, 1994), whereas our findings (45° ± 12°) align with recent research on flatter breaststroke techniques (Gourgoulis et al., 2018; Seifert et al., 2014).

The non-breathing cycle showed the highest peak CoM velocity in the swimming direction and the highest maximum vertical velocity of the feet, suggesting that not breathing may enhance foot propulsion and contribute to greater peak CoM velocity. However, these gains did not translate into differences in overall mean or minimum CoM velocities. A likely explanation is that although swimmers reach higher velocities during the propulsive phase of the non-breathing cycle, subsequent phases reduce velocity to levels comparable to those of other cycles. This interpretation is supported by the lack of differences in mean CoM velocity in both the SPM analysis and dv values.

The breathing cycle showed greater medio-lateral hand amplitude, and a lower minimum vertical CoM velocity compared to the breathing cycle following a non-breathing cycle. This suggests that breathing may lead to increased hand displacement, potentially enhancing propulsion. However, the reduced hand amplitude in the cycle following a non-breathing one may indicate a lingering effect that limits propulsive effectiveness. The lower minimum vertical CoM velocity during the breathing cycle could reflect a greater loss of momentum, possibly due to increased drag from lifting the head. Still, these changes did not impact dv, which remained consistent across cycles.

The results from **Chapter 5** revealed no differences in dv and FD between the breathing patterns. Additionally, both parameters showed lower values compared to those reported in the literature. This discrepancy may be attributed to the high variability within the sample, likely influenced by differences in technical proficiency and skill level among the swimmers. Indeed, previous research demonstrated that swimmer expertise impacts motor system complexity, with highly skilled, expert, and non-expert swimmers presenting FD values of 1.84 ± 0.08, 1.85 ± 0.09, and 1.89 ± 0.06, respectively (Barbosa et al., 2017b). Moreover, the low coefficient of variation values observed in this study may be linked to the fact that the sample included young swimmers with relatively low competitive levels. These swimmers may lack the capacity to produce pronounced accelerations, resulting in reduced dv. Furthermore, the three cycle types exhibited similar velocity variations, suggesting that the breathing pattern did not substantially influence dv.

Following the observations in **Chapter 5**, which highlighted the absence of differences in dv and FD between breathing patterns, **Chapter 6** further explores the efficiency of breaststroke swimming and its relationship with energy cost and D_{a}, while considering the breathing patterns. While dv and FD, studied in **Chapter 5**, are indicative of motor variability and movement complexity, efficiency indices provide a more direct assessment of how effectively a swimmer converts metabolic energy into forward motion. Both types of parameters, kinematic and energetic, offer complementary insights into the swimmer's performance. As such, **Chapter 6** aimed to bridge these biomechanical and energetic perspectives by introducing adapted indices of efficiency (hand, foot, and global), and stabilization for breaststroke, and investigating their association with C and D_{a}. This integrated analysis allows a deeper understanding of how breathing patterns affect not only movement patterns and variability (as shown in **Chapter 5**) but also mechanical efficiency and their energetic and drag relationships.

Breathing every cycle resulted in greater hand efficiency, as well as higher hand antero-posterior and total hand antero-posterior stabilization indices, suggesting that reducing breathing frequency may slightly impair hand motor path technique. This may stem from the increased head and trunk movements during breathing, which could help maintain stroke rhythm and coordination, potentially enhancing upper limb propulsion, especially during the insweep phase. These findings are supported by the ones in **Chapter 5**, where the breathing cycle exhibited greater medio-lateral hand amplitude, indicating that breathing may increase hand displacement and thereby improve propulsion. While reduced breathing frequency is often thought to minimize technical disruption and improve efficiency in front crawl (Psycharakis & McCabe, 2011), our results suggest that, in breaststroke, the standard pattern of breathing every cycle may better support effective hand propulsion.

Breathing every two cycles was associated with a higher total foot antero-posterior stabilization index and greater foot displacement, suggesting that while reduced breathing frequency may slightly decrease upper limb propulsion, it could enhance propulsion from the lower limbs. These findings align with **Chapter 5**, where the non-breathing cycle exhibited the greatest maximum vertical velocity of the feet, indicating that not breathing may improve foot propulsion.

Unlike front crawl, where propulsion primarily comes from the arms (Morouço et al., 2015), breaststroke depends heavily on the lower limbs for propulsion (Mason et al., 1989; Kippenhan, 2002; Shahbazi-Moghadam, 2008). Therefore, assessing foot efficiency alongside hand efficiency is crucial for a complete understanding of propulsive effectiveness in breaststroke. In this thesis, a time-series approach was introduced to estimate efficiency continuously throughout the stroke cycle, rather than relying on discrete mean values for the entire cycle. This provides a more detailed characterization of individual technique, allowing for the identification of specific moments within the cycle where improvements may be needed or achievable. Such an approach holds relevance not only for different breaststroke breathing patterns but, potentially, with proper adaptation, also for other swimming techniques. These analyses revealed that efficiency values occasionally exceeded one, indicating moments when the CoM velocity surpassed that of the hands or feet, eventually due to a combined effect of both on swimming velocity. Nevertheless, these indices should not be interpreted as absolute measures, since values above unity conflict with the theoretical definition of efficiency.

By combining hand and foot efficiency, we derived a global efficiency index that provides a comprehensive assessment of overall propulsion in breaststroke. In **Chapter 6**, $\eta_{F.global}$ was calculated as the ratio between the velocity of the propulsive segments and that of the swimmer's center of mass, without explicitly accounting for the hydrodynamic drag force and the total external propulsive force. Since these forces are not equivalent and cannot be mathematically canceled from the theoretical efficiency equation, this simplification limits direct comparability with true mechanical (Froude) efficiency. Consequently, this speed-based approach may not fully capture the mechanical aspects underlying Froude efficiency, which may help explain the weak correlations observed.

In the analysis of the $\eta_{F.global}$ and its relationship with $\dot{E}_{tot}$, Da, and v, the slopes of the individual regression lines were remarkably consistent across swimmers. The inter-individual variability likely explains the deviations observed from the line of identity in Figure 3 of **Chapter 6**, which represents the theoretical relationship derived from di Prampero's equation using total mechanical efficiency. Points above the identity line indicate relatively higher values of D / $\eta_{F,global}$ compared to D / η_d. Since D remains constant, this implies that $\eta_{F,global}$ exceeds η_d, reflecting lower energy losses through heat, internal work, or energy transferred to the water mass. Conversely, points below the line denote relatively greater energy dissipation. Because points above the line remain thermodynamically coherent, these findings support the theoretical soundness of our approach to η_F. Notably, most swimmers and conditions presented slopes close to one, either slightly above or slightly below, indicating that energy cost and the ratio D / $\eta_{F,global}$ are proportional to D / η_d. This reinforces the assumption that energy lost as heat, internal work, and changes in the water's mechanical energy are relatively consistent across individuals and conditions. Nonetheless, small deviations were evident and warrant further investigation.

As part of the analyses presented in **Chapter 6**, we applied the indices originally proposed by Vilas-Boas (1993) to indirectly assess movement efficiency in the breaststroke technique. The overall goal of these indices is to infer whether swimmers are primarily using propulsive drag, pushing water directly backwards (Counsilman, 1968; Hay, 1986; Maglischo, 1982), or relying more on lift-based propulsion, which involves oblique and transverse limb movements (Counsilman, 1969, 1971; Schleihauf, 1974, 1976, 1979). The hand motor paths showed predominantly medio-lateral movement, while foot motor paths were mainly vertical. This pattern was confirmed by the antero-posterior and total antero-posterior stabilization indices, which indicated greater stabilization in the hands compared to the feet. This reinforces the distinction between the predominantly antero-posterior and medio-lateral movements of the hands and the primarily vertical motions of the feet. Notably, C correlated moderately and negatively with the hand antero-posterior stabilization index, and $\dot{E}_{tot}$ correlated moderately and negatively with the total antero-posterior stabilization index, suggesting that greater motor path stabilization is associated with lower energy demands.

The foot displacement index reflects how the swimmer was able to complete the movement with the feet positioned further forward relative to the starting point, suggesting effective stabilization and forward propulsion of the body. Results showed that, although the center of mass advanced, the feet remained close to their starting position. Importantly, this measure can be easily used in daily training to visually evaluate foot motor path efficiency, helping coaches identify whether the feet effectively push forward or merely move backward, indicating an ineffective lower limbs action.

The differences in bioenergetic variables observed in **Chapter 3** between breathing patterns are closely linked to the swimmers' kinematic and hydrodynamic characteristics analyzed in **Chapters 4**, **5**, and **6**. Variations in motor path stabilization and propulsion, as reflected in hand and foot efficiency indices, influence the swimmer's ability to maintain velocity with minimal C. Greater stabilization of motor paths, particularly in the hands, correlated with lower C and $\dot{E}_{tot}$, underscoring the critical role of technical execution in bioenergetic efficiency. This suggests that swimmers who maintain a more consistent and controlled limb trajectory are better able to convert energy into effective propulsion while minimizing unnecessary movements that increase energy expenditure. In contrast, the D_a, although theoretically related to C, did not show an association with the efficiency and stabilization indices in **Chapter 6**.

It is plausible that the time allocated to adapting to the alternate breathing pattern was insufficient for some swimmers to optimize their technique. As a result, they may have performed more efficiently with the breathing pattern they were already familiar with and had practiced extensively. This is supported by the individual variability observed in

Chapters 3 and **4**, where some swimmers showed improved energy demands and lower active drag when breathing every two cycles, while others performed better breathing every cycle. Additionally, the variability within the sample may have influenced the overall results, contributing to the absence of significant differences at the group level. This heterogeneity may stem from differences in swimmers' skill levels, physiological characteristics, and technical proficiency, all of which can affect how individuals respond to different breathing patterns. To mitigate these confounding effects, statistical approaches such as ANCOVA and partial correlations were employed to control factors including performance level (World Aquatics points), age, and swimming velocity. These methods helped isolate the specific influence of breathing pattern on the measured variables, improving the robustness of the findings.

Overall, the present work provides a comprehensive view of how biomechanics, energetics, and hydrodynamics interact under different breathing conditions in the breaststroke technique. The systematic review highlighted the scarcity of studies addressing energetics and hydrodynamic drag, as well as the lack of integrative approaches combining multiple domains, which guided the design of the subsequent experimental chapters. In **Chapter 3**, a reduced breathing pattern was associated with higher $\dot{V}O_2$ peak and [La^-], raising the question of which variables could explain these responses. **Chapter 4** showed that active drag was not consistently affected by breathing frequency, while **Chapter 5** demonstrated that intracyclic velocity variation and fractal dimension were also not substantially influenced. Although some kinematic variables differed between conditions in **Chapter 5**, these changes were minimal and did not point to a clear advantage of either breathing pattern. **Chapter 6** advanced this analysis by introducing adapted efficiency indices, revealing individual differences in how efficiency and energy cost relate to drag under different breathing strategies. Together, these findings indicate that no single breathing pattern is universally superior; rather, responses are highly individual, with some swimmers benefitting from reduced breathing, while others perform more efficiently with the mainstream breathing every cycle. From a practical standpoint, these results reinforce the need for individualized technical adjustments, combining energetic, hydrodynamic, and kinematic assessments to optimize performance.

Chapter 8. Conclusions

In this section, we synthesize the key insights and implications emerging from our comprehensive investigation of energetics, active drag, and kinematics in breaststroke swimming. The following conclusions encapsulate the main findings of our research and highlight their relevance for advancing swimming performance:

(i.) Literature reports that, among the four competitive techniques, breaststroke shows the highest active drag, frontal surface area, and energy cost, as well as the lowest swimming velocities.

(ii.) Literature further indicates that variability in the energy cost of breaststroke is strongly determined by stroke kinematics, particularly stroke rate, stroke length, stroke index, and intra-cyclic velocity fluctuation.

(iii.) Breathing every two cycles in breaststroke is associated with higher values of peak blood lactate concentration, peak oxygen uptake, energy expenditure, and energy cost, particularly at moderate intensities.

(iv.) Individual variability was observed in swimmers' hydrodynamic responses to different breathing patterns in breaststroke.

(v.) The non-breathing cycle had the shallowest and deepest head positions, the lowest horizontal head amplitude out of water, and the smallest vertical head amplitude.

(vi.) This cycle also corresponded with the highest maximum vertical foot velocity and greatest maximal center of mass velocity in the swimming direction, indicating potential biomechanical advantages.

(vii.) Breathing every cycle showed greater medio-lateral hand amplitude and lower minimum center of mass horizontal velocity.

(viii.) Breathing every cycle enhanced hands' efficiency and hands' stabilization measures, while breathing every two cycles improved feet stabilization and displacement.

(ix.) Greater motor path stabilization is associated with lower energy cost, while feet and total stabilization indices strongly relate to feet displacement.

Overall, the breaststroke technique is only minimally influenced by the breathing pattern. While subtle changes in head, hands, and feet kinematics occur, these do not lead to substantial differences in performance. However, some swimmers showed individual benefits from a reduced breathing frequency, suggesting that the impact of breathing pattern may depend on individual characteristics and adaptations.

Chapter 9. Suggestions for future research

The primary objective of this dissertation was to compare and characterize two breathing patterns, breathing every cycle and breathing every two cycles, in the breaststroke technique. Considering our findings, we believe it is paramount to continue researching this topic, with a specific focus on:

(i.) Exploring alternative breathing strategies, such as breathing every three cycles or allowing swimmers to adopt a self-selected breathing pattern. These approaches could offer a more individualized understanding of how swimmers can naturally adapt breathing to optimize performance.

(ii.) The inclusion of a more homogeneous sample, such as swimmers with intermediate expertise, that could reduce variability and yield clearer conclusions regarding the impact of subtle technique modifications such as breathing frequency.

(iii.) Increasing the sample size and ensuring balanced representation across sexes may help to identify potential sex-related differences in physiological and biomechanical responses to different breathing strategies.

(iv.) The use of an incremental protocol based on 200 m efforts may limit the ability to extrapolate findings to higher-intensity, short-distance events such as the 50 m and 100 m races. Alternative protocols tailored to sprint distances could provide more specific insights into performance under maximal or near-maximal effort conditions.

(v.) Investigating whether modifications in the intervention period, such as longer adaptation phases, might enhance the effectiveness and adoption of new breathing patterns.

(vi.) Examining the impact of breathing strategies on coordination variables in breaststroke.

Chapter 10. References

Chapter 1

Abarbanel, H. D., Rabinovich, M. I., & Sushchik, M. M. (1993). Introduction to nonlinear dynamics for physicists (Vol. 53). *World scientific*.

Alves, F., Cunha, P., Gomes-Pereira, J. (1999). Kinematic changes with inspiratory actions in butterfly swimming. In: Keskinen KL, Komi PV, Hollander AP (eds). *Biomechanics and medicine in swimming VIII*. Finland, Jyvaskyla: University of Jyvaskyla. 9 – 14.

Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. *Journal of science and medicine in sport*, *13*(2), 262-269.

Barbosa, T. M., Keskinen, K. L., Fernandes, R., Colaço, P., Lima, A. B., & Vilas-Boas, J. P. (2005). Energy cost and intracyclic variation of the velocity of the centre of mass in butterfly stroke. *European journal of applied physiology*, *93*, 519-523.

Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European journal of applied physiology and occupational physiology*, *78*(5), 385-393.

Capelli, C., Zamparo, P., Cigalotto, A., Francescato, M. P., Soule, R. G., Termin, B. & Di Prampero, P. E. (1995). Bioenergetics and biomechanics of front crawl swimming. *Journal of applied physiology*, *78*(2), 674-679.

Clarys, J. P. (1979). Human morphology and hydrodynamics. *Swimming III*, *8*, 3-41.

Costill, D. L., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., & King, D. (1985). Energy expenditure during front crawl swimming: predicting success in middle-distance events. *International journal of sports medicine*, 6(05), 266-270.

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.

Craig Jr, A. B., & Pendergast, D. R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine and science in sports*, 11(3), 278-283.

Daniel, T. L. (1991). Efficiency in aquatic locomotion: limitations from single cells to animals. *Efficiency and economy in animal physiology*, 83-95.

di Prampero, P. E. (1986). The energy cost of human locomotion on land and in water. *International journal of sports medicine*, *7*(02), 55-72.

di Prampero, P. E., Capelli, C., Pagliaro, P., Antonutto, G., Girardis, M., Zamparo, P., & Soule, R. G. (1993). Energetics of best performances in middle-distance running. Journal of Applied Physiology, 74(5), 2318-2324.

di Prampero, P. E., Pendergast, D. R., Wilson, D. W., & Rennie, D. W. (1974). Energetics of swimming in man. *Journal of applied physiology*, 37(1), 1-5.

Dicker, S. G., Lofthus, G. K., Thornton, N. W., & Brooks, G. A. (1980). Respiratory and heart rate responses to tethered controlled frequency breathing swimming. *Medicine and science in sports and exercise*, 12(1), 20-23

Figueiredo P, Toussaint HM, Vilas-Boas JP, Fernandes RJ (2013) Relation between efficiency and energy cost with coordination in aquatic locomotion. *European journal of applied physiology,* 113:651–659

Figueiredo, P., Kjendlie, P. L., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Intracycle velocity variation of the body centre of mass in front crawl. *International journal of sports medicine*, 33(04), 285-290.

Gatta, G., Cortesi, M., Fantozzi, S., & Zamparo, P. (2015). Planimetric frontal area in the four swimming strokes: Implications for drag, energetics and speed. *Human movement science*, 39, 41-54.

Gonjo, T., McCabe, C., Sousa, A., Ribeiro, J., Fernandes, R. J., Vilas-Boas, J. P., & Sanders, R. (2018). Differences in kinematics and energy cost between front crawl and backstroke below the anaerobic threshold. *European journal of applied physiology*, 118, 1107-1118.

Gourgoulis, V., Koulexidis, S., Gketzenis, P., & Tzouras, G. (2018). Intracyclic Velocity Variation of the Center of Mass and Hip in Breaststroke Swimming with Maximal Intensity. *The journal of strength & conditioning research*, 32(3), 830-840.

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.

Higuchi, T. (1988). Approach to an irregular time series on the basis of the fractal theory. *Physica D: nonlinear phenomena*, 31(2), 277-283.

Holmer I (1974) Physiology of swimming man. *Acta physiologica scandinavica*, [Suppl] 407:1-55.

Holmer I, Gullstrand L (1980) Physiological responses to swimming with a controlled frequency of breathing. *Scandinavian journal of medicine & science in sports*, 2: 1-6.

Kapus J, Usaj A, Kapus V, Strumbelj B (2003) Influence of reduced breathing during swimming on some respiratory and metabolic values in blood. *KinSl,* 9: 12-17.

Key, M. A., Eschbach, C. L., & Bunn, J. A. (2014). Assessment of the effects of controlled frequency breathing on lactate levels in swimming*. Journal of athletic enhancement*, 3, 5, 2.

Kolmogorov, S. V., & Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of biomechanics*, 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. *Journal of applied biomechanics*, 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. *Applied sciences*, 11(18), 8511.

Leblanc, H., Seifert, L., Baudry, L., & Chollet, D. (2005). Arm-leg coordination in flat breaststroke: A comparative study between elite and non-elite swimmers. *International journal of sports medicine*, 26(9), 787–797.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic distance per stroke phase, velocity fluctuations and acceleration time ratio of a breaststroker's hip: A comparison between elite and nonelite swimmers at different race paces. *International journal of sports medicine*, 28(02), 140-147.

Maglischo, C. W., Maglischo, E. W., & Santos, T. R. (1987). The relationship between the forward velocity of the center of gravity and the forward velocity of the hip in the four competitive strokes. *Journal of swimming research*, 3(2), 11-17.

Martin, R. B., Yeater, R. A., & White, M. K. (1981). A simple analytical model for the crawl stroke. *Journal of biomechanics*, 14(8), 539-548.

Miller, D. I. (1975). Biomechanics of swimming. *Exercise and sport sciences reviews*, 3(1), 219-248.

Murlasits, Z., Laszlo, S., Prokai, J., Sebesi, B., Scherer, J., Tovari, F. & Vaczi, M. (2023). Physiological responses to an incremental swim test with different breathing frequencies in competitive male youth swimmers. *Journal of physical education and sport*, 23(3), 697-703

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., Zamparo, P., di Prampero, P. E., Capelli, C., Cerretelli, P., Termin, A., & Mollendorf, J. (2003). Energy balance of human locomotion in water. *European journal of applied physiology*, 90, 377-386.

Peterson-Silveira R, de Souza Castro F, Figuereido P, Vilas-Boas JP, Zamparo P (2017) The effects of leg kick on swimming speed and arm-stroke efficiency in the front crawl. *International journal of sports physiology and performance*, 12(6):728–735

Psycharakis, S. G., & Sanders, R. H. (2009). Validity of the use of a fixed point for intracycle velocity calculations in swimming. *Journal of science and medicine in sport*, 12(2), 262-265.

Sammoud, S., Nevill, A. M., Negra, Y., Bouguezzi, R., Chaabene, H., & Hachana, Y. (2018). 100-m breaststroke swimming performance in youth swimmers: The predictive value of anthropometrics. *Pediatric exercise science*, 30(3), 393-401.

Seifert L, Komar J, Crettenand F, Millet G (2014) Coordination pattern adaptability: energy cost of degenerate behaviors. *PLoS One*, 9(9): e107839.

Seifert, L., & Chollet, D. (2005). A new index of flat breaststroke propulsion: A comparison of elite men and women. *Journal of sports sciences*, 23(3), 309–320.

Seifert, L., Chollet, D., & Sanders, R. (2010). Does breathing disturb coordination in butterfly?. *International journal of sports medicine*, 31(03), 167-173.

Seifert, L., Komar, J., Barbosa, T., Toussaint, H., Millet, G., & Davids, K. (2014). Coordination pattern variability provides functional adaptations to constraints in swimming performance. *Sports medicine*, 44, 1333-1345.

Van Tilborgh, L., Willems, E. J. W., & Persyn, U. (1988). Estimation of breaststroke propulsion and resistance resultant impulses from film analysis. *Swimming science V (International series on sport sciences 18), Champaign (Ilinois): Human Kinetics*, 67-72.

Toussaint, H. M., & Beek, P. J. (1992). Biomechanics of competitive front crawl swimming. *Sports medicine*, 13, 8-24.

Toussaint, H. M., & Hollander, A. P. (1994). Energetics of competitive swimming: implications for training programmes. *Sports medicine*, 18, 384-405.

Toussaint, H. M., Beelen, A., Rodenburg, A., Sargeant, A. J., de Groot, G., Hollander, A. P., & van Ingen Schenau, G. J. (1988). Propelling efficiency of front-crawl swimming. *Journal of applied physiology*, 65(6), 2506-2512.

Toussaint, H. M., Janssen, T., & Kluft, M. (1989). The influence of paddles on propulsion. *Swimming technique*, 26(2), 28-32.

Toussaint, H., & Truijens, M. (2005). Biomechanical aspects of peak performance in human swimming. *Animal biology*, 55(1), 17-40.

Vilas-Boas JP (1996) Speed fluctuations and energy cost of different breaststroke techniques. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA (eds) *Biomechanics and medicine in swimming* VII. E & FN Spon, London, pp167–171

Vilas-Boas, J. P. (1993). Caracterização biofísica de três variantes da técnica de bruços (Ph.D Thesis, University of Porto). Porto, *Medisa - edições e divulgações científicas*, Lda. (ISBN: 972-8105-02-9).

Vilas-Boas JP, Santos P (1994) Comparison of swimming economy in three breaststroke techniques. In: Miyashita M, Richardson AB (eds) *Medicine and science in aquatic sports*. Kargel, Basel, pp 48–54

Webb, P. W. (1971). The swimming energetics of trout: II. Oxygen consumption and swimming efficiency. *Journal of experimental biology*, *55*(2), 521-540.

West, S. A., Drummond, M. J., VanNess, J. M., & Ciccolella, M. E. (2005). Blood lactate and metabolic responses to controlled frequency breathing during graded swimming. *The journal of strength & conditioning research*, 19(4), 772-776.

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. *Journal of sports sciences*, 25(4), 375-379.

Zamparo, P. (2006). Effects of age and gender on the propelling efficiency of the arm stroke. *European journal of applied physiology*, 97(1), 52-58.

Zamparo, P., Cortesi, M., & Gatta, G. (2020). The energy cost of swimming and its determinants. *European journal of applied physiology*, *120*, 41-66.

Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A., & Minetti, A. E. (2005). An energy balance of front crawl. *European journal of applied physiology*, 94, 134-144.

Zamparo, P., Pendergast, D. R., Termin, B., & Minetti, A. E. (2002). How fins affect the economy and efficiency of human swimming. *Journal of Experimental Biology*, *205*(17), 2665-2676.

Zamparo, P., Turri, E., Peterson Silveira, R., & Poli, A. (2014). The interplay between arms-only propelling efficiency, power output and speed in master swimmers. *European journal of applied physiology*, 114, 1259-1268.

Zompanakis, I., Papadimitriou, K., Georgios, T., & Dimitrios, L. (2021). The effects of reduced breathing on swimming performance and on blood lactate concentration in 25 and 50 m breaststroke swimming at maximal intensity. *in international conference of sports science- AESA* (No. 4).

Chapter 2

Arellano, R., Ruiz-Navarro, J. J., Barbosa, T. M., López-Contreras, G., Morales-Ortíz, E., Gay, A., ... & Cuenca-Fernández, F. (2022). Are the 50 m race segments changed from heats to finals at the 2021 european swimming championships?. *Frontiers in physiology*, 1337.

Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010a). Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. *Journal of science and medicine in sport*, 13(2), 262-269.

Barbosa, T. M., Fernandes, R. J., Keskinen, K. L., & Vilas-Boas, J. P. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European journal of applied physiology*, *103*(2), 139-149.

Barbosa, T. M., Fernandes, R., Keskinen, K. L., Colaço, P., Cardoso, C., Silva, J., & Vilas-Boas, J. P. (2006). Evaluation of the energy expenditure in competitive swimming strokes. *International journal of sports medicine*, *27*(11), 894-899.

Barbosa, T. M., Goh, W. X., Morais, J. E., & Costa, M. J. (2017). Variation of linear and nonlinear parameters in the swim strokes according to the level of expertise. *Motor control*, *21*(3), 312-326.

Barbosa, T. M., Goh, W. X., Morais, J. E., Costa, M. J., & Pendergast, D. (2016). Comparison of classical kinematics, entropy, and fractal properties as measures of complexity of the motor system in swimming. *Frontiers in psychology*, *7*, 1566.

Barbosa, T. M., Morouço, P. G. F., Jesus, S., Feitosa, W. G., Costa, M. J., Marinho, D. A. & Garrido, N. D. (2013). The interaction between intra-cyclic variation of the velocity and mean swimming velocity in young competitive swimmers. *International journal of sports medicine*, *34*(02), 123-130.

Barbosa, T., Silva, A. J., Reis, A. M., Costa, M., Garrido, N., Policarpo, F., & Reis, V. M. (2010b). Kinematical changes in swimming front Crawl and Breaststroke with the AquaTrainer® snorkel. *European journal of applied physiology*, *109*(6), 1155-1162.

Bartolomeu, R. F., Costa, M. J., & Barbosa, T. M. (2018). Contribution of limbs' actions to the four competitive swimming strokes: a nonlinear approach. *Journal of sports sciences*, *36*(16), 1836-1845.

Bonifazi, M., Martelli, G., Marugo, L., Sardella, F., & Carli, G. (1993). Blood lactate accumulation in top level swimmers following competition. *The journal of sports medicine and physical fitness*, 33(1), 13-18.

Bravi, A., Longtin, A., and Seely, A. J. (2011). Review and classification of variability analysis techniques with clinical applications. *BioMedical engineering onLine*, 10:90.

Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European journal of applied physiology and occupational physiology*, *78*(5), 385-393.

Carvalho, D. D., Soares, S., Zacca, R., Sousa, J., Marinho, D. A., Silva, A. J., ... & Fernandes, R. J. (2020). Anaerobic threshold biophysical characterisation of the four swimming techniques. *International journal of sports medicine*, *41*(05), 318-327.

Chatard, J. C., Collomp, C., Maglischo, E., & Maglischo, C. (1990). Swimming skill and stroking characteristics of front crawl swimmers. *International journal of sports medicine*, 11(02), 156-161.

Chollet, D., Pelayo, P., Tourny, C., & Sidney, M. (1996). Comparative analysis of 100m and 200m events in the four strokes in top level swimmers. *Journal of human movement studies*, *31*, 25-37.

Chollet, D., Seifert, L., Leblanc, H., Boulesteix, L., & Carter, M. (2004). Evaluation of arm-leg coordination in flat breaststroke. *International journal of sports medicine*, *25*(07), 486-495.

Cohen, R. C., Cleary, P. W., Harrison, S. M., Mason, B. R., & Pease, D. L. (2014). Pitching effects of buoyancy during four competitive swimming strokes. *Journal of applied biomechanics*, *30*(5), 609-618.

Colman, V., Persyn, U., Daly, D., & Stijnen, V. (1998). A comparison of the intra-cyclic velocity variation in breaststroke swimmers with flat and undulating styles. *Journal of sports sciences*, *16*(7), 653-665.

Conceição, A., Silva, A. J., Boaventura, J., Marinho, D. A., & Louro, H. (2013b). Wave characteristics in breaststroke technique with and without snorkel use. *Journal of human kinetics*, *39*, 185.

Conceição, A., Silva, A., Barbosa, T. M., & Louro, H. (2013a). Observation and technical characterization in swimming: 200 m breaststroke. *Revista Brasileira de Medicina do Esporte*, *19*, 56-61.

Costill, D. L., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., & King, D. (1985). Energy expenditure during front crawl swimming: Predicting success in middle-distance events. *International journal of sports medicine*, 6(05), 266–270.

Craig, A. B., Boomer, W. L., & Skehan, P. L. (1988). Patterns of velocity in competitive breaststroke swimming. *Swimming science*, 18, 73–77.

Craig Jr, A. B., & Pendergast, D. R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine and science in sports*, *11*(3), 278-283.

Craig Jr, A. B., Skehan, P. L., Pawelczyk, J. A., & Boomer, W. L. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine and science in sports and exercise*, 17(6), 625-634.

Cuenca-Fernández, F., Ruiz-Navarro, J. J., Polach, M., Arellano, R., & Born, D. P. (2023). Short-course performance variation across all race sections: How 100 and 200 m elite male swimmers progress between rounds. *Frontiers in Sports and Active Living*, 5, 1146711.

D'Aquisto, L. J., Costill, D. L., Gehlson, G. M., Wong-Tai Young, M. A., & Ang, G. L. (1988). Breaststroke swimming economy, skill and performance: study of breaststroke mechanics using a computer based" velocity video" system. *Journal of swimming research*, 4, 9-13.

Di Prampero, P. E., Dekerle, J., Capelli, C., & Zamparo, P. (2008). The critical velocity in swimming. *European journal of applied physiology*, *102*(2), 165-171.

Di Prampero, P. E., Pendergast, D. R., Wilson, D. W., & Rennie, D. W. (1974). Energetics of swimming in man. *Journal of applied physiology*, 37(1), 1-5.

Gatta, G., Cortesi, M., Fantozzi, S., & Zamparo, P. (2015). Planimetric frontal area in the four swimming strokes: Implications for drag, energetics and speed. *Human movement science*, *39*, 41-54.

Gonjo, T., & Olstad, B. H. (2023). Differences between elite and sub-elite swimmers in a 100 m breaststroke: a new race analysis approach with time-series velocity data. *Sports biomechanics*, 22(12), 1722-1733.

Gourgoulis, V., & Nikodelis, T. (2022). Comparison of the arm-stroke kinematics between maximal and sub-maximal breaststroke swimming using discrete data and time series analysis. *Journal of biomechanics*, *142*, 111255.

Gourgoulis, V., Koulexidis, S., Gketzenis, P., & Tzouras, G. (2018). Intracyclic velocity variation of the center of mass and hip in breaststroke swimming with maximal intensity. *The journal of strength & conditioning research*, *32*(3), 830-840.

Hellard, P., Dekerle, J., Avalos, M., Caudal, N., Knopp, M., & Hausswirth, C. (2008). Kinematic measures and stroke rate variability in elite female 200-m swimmers in the four swimming techniques: Athens 2004 Olympic semi-finalists and French National 2004 championship semi-finalists. *Journal of sports sciences*, *26*(1), 35-46.

Hermosilla, F., Corral-Gómez, L., González-Ravé, J. M., Juárez Santos-García, D., Rodríguez-Rosa, D., Juárez-Pérez, S., & Castillo-Garcia, F. J. (2020). SwimOne. New device for determining instantaneous power and propulsive forces in swimming. *Sensors*, *20*(24), 7169.

Hindle, B. R., Lorimer, A., Winwood, P., & Keogh, J. W. (2019a). A systematic review of the biomechanical research methods used in strongman studies. *Sports biomechanics*.

Hindle, B. R., Lorimer, A., Winwood, P., & Keogh, J. W. (2019b). The biomechanics and applications of strongman exercises: a systematic review. *Sports medicine-open*, 5(1), 1-19.

Holfelder, B., Brown, N., & Bubeck, D. (2013). The influence of sex, stroke and distance on the lactate characteristics in high performance swimming. *PloS one*, *8*(10), e77185.

Hollander, A. P., De Groot, G., van Ingen Schenau, G. J., Toussaint, H. M., De Best, H., Peeters, W. & Schreurs, A. W. (1986). Measurement of active drag during crawl arm stroke swimming. *Journal of sports sciences*, 4(1), 21-30.

Holmér, I. (1974a). Energy cost of arm stroke, leg kick, and the whole stroke in competitive swimming styles. *European journal of applied physiology and occupational physiology*, *33*(2), 105-118.

Holmér, I. (1974b). Propulsive efficiency of breaststroke and freestyle swimming. *European journal of applied physiology and occupational physiology*, *33*(2), 95-103.

Holmér, I. (1992). Swimming physiology. *The Annals of physiological anthropology*, *11*(3), 269-276.

Kolmogorov, S. V., & Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of biomechanics*, *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. *Journal of applied biomechanics*, *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. *Applied sciences*, 11(18), 8511.

Komar, J., Sanders, R. H., Chollet, D., & Seifert, L. (2014). Do qualitative changes in interlimb coordination lead to effectiveness of aquatic locomotion rather than efficiency?. *Journal of applied biomechanics*, *30*(2), 189-196.

Lauer, J., Olstad, B. H., Minetti, A. E., Kjendlie, P. L., & Rouard, A. H. (2015). Breaststroke swimmers moderate internal work increases toward the highest stroke frequencies. *Journal of biomechanics*, *48*(12), 3012-3016.

Leblanc, H., Seifert, L., & Chollet, D. (2009). Arm–leg coordination in recreational and competitive breaststroke swimmers. *Journal of science and medicine in sport*, *12*(3), 352-356.

Leblanc, H., Seifert, L., & Chollet, D. (2010). Does floatation influence breaststroke technique?. *Journal of applied biomechanics*, *26*(2), 150-158.

Leblanc, H., Seifert, L., Baudry, L., & Chollet, D. (2005). Arm-leg coordination in flat breaststroke: a comparative study between elite and non-elite swimmers. *International journal of sports medicine*, *26*(09), 787-797.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic distance per stroke phase, velocity fluctuations and acceleration time ratio of a breaststroker's hip: a comparison between elite and nonelite swimmers at different race paces. *International journal of sports medicine*, *28*(02), 140-147.

Lomax, M., Royal, J. T., Kapus, J., Massey, H., & Saynor, Z. (2022). Oxygen uptake kinetics and ventilatory and metabolic parameters do not differ between moderate-intensity front crawl and breaststroke swimming. *Physiological Reports*, *10*(12), e15361.

Maglischo, E. W. (1993). Swimming even faster. Ed. *Mayfield Publishing Company*, California, USA.

Manley, P. K., & Atha, J. (1992). Intra-stroke velocity fluctuations in paced breaststroke swimming. In D. Maclaren, T. Reilly, & A. Lee (Eds.), *Swimming science VI* (pp. 151–159). London: E. and F. N. Spon.

Marinho, D. A., Amorim, R. A., Costa, A. M., Marques, M. C., Pérez-Turpin, J. A., & Neiva, H. P. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *Journal of human sport and exercise*, *6*(1), 80-86.

Mason, B., Patton, S., & Newton, A. (1989). Propulsion in breaststroke swimming. In *ISBS-Conference Proceedings Archive*.

Mason, B., Sacilotto, G., & Menzies, T. (2011). Estimation of active drag using an assisted tow of higher than max swim velocity that allows fluctuating velocity & varying tow force. In *ISBS-Conference Proceedings Archive*.

Methley, A. M., Campbell, S., Chew-Graham, C., McNally, R., & Cheraghi-Sohi, S. (2014). PICO, PICOS and SPIDER: a comparison study of specificity and sensitivity in three search tools for qualitative systematic reviews. *BMC health services research, 14*(1), 1-10.

Morouço, P., Keskinen, K. L., Vilas-Boas, J. P., & Fernandes, R. J. (2011). Relationship between tethered forces and the four swimming techniques performance. *Journal of applied biomechanics*, *27*(2), 161-169.

Natera, A. O., Cardinale, M., & Keogh, J. W. (2020). The effect of high volume power training on repeated high-intensity performance and the assessment of repeat power ability: a systematic review. *Sports Medicine*, 50(7), 1317-1339.

Nicol, E., Pearson, S., Saxby, D., Minahan, C., & Tor, E. (2022). Stroke kinematics, temporal patterns, neuromuscular activity, pacing and kinetics in elite breaststroke swimming: a systematic review. *Sports Medicine-Open*, 8(1), 1-24.

Oliveira, D. R., Gonçalves, L. F., Reis, A. M., Fernandes, R. J., Garrido, N. D., & Reis, V. M. (2016). The oxygen uptake slow component at submaximal intensities in breaststroke swimming. *Journal of human kinetics*, *51*(1), 165-173.

Oliveira, J. P., Marinho, D. A., Barbosa, T. M., Sampaio, T., & Morais, J. E. (2023). Profile of female swimmers competing in the 50 m events at the 2021 LEN European Championships. *International journal of performance analysis in sport*, 23(2), 97-110.

Olstad, B. H., Vaz, J. R., Zinner, C., Cabri, J. M., & Kjendlie, P. L. (2017). Muscle coordination, activation and kinematics of world-class and elite breaststroke swimmers during submaximal and maximal efforts. *Journal of sports sciences*, *35*(11), 1107-1117.

Olstad, B. H., Wathne, H., & Gonjo, T. (2020). Key factors related to short course 100 m breaststroke performance. *International journal of environmental research and public health*, *17*(17), 6257.

Oxford, S. W., James, R. S., Price, M. J., Payton, C. J., & Duncan, M. J. (2017). Changes in kinematics and arm–leg coordination during a 100-m breaststroke swim. *Journal of sports sciences*, *35*(16), 1658-1665.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D. & Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *International Journal of Surgery*, 88, 105906.

Pai, Y. C., Hay, J. G., & Wilson, B. D. (1984). Stroking techniques of elite swimmers. *Journal of sports sciences*, *2*(3), 225-239.

Pincus, S. M. (1991). Approximate entropy as a measure of system complexity. *Proceedings of the national academy of sciences*, *88*(6), 2297-2301.

Psycharakis, S. G., Cooke, C. B., Paradisis, G. P., O'Hara, J., & Phillips, G. (2008). Analysis of selected kinematic and physiological performance determinants during incremental testing in elite swimmers. *The journal of strength & conditioning research*, *22*(3), 951-957.

Reis, V. M., Barbosa, T. M., Marinho, D. A., Policarpo, F., Reis, A. M., & Silva, A. J. (2010). Physiological determinants of performance in breaststroke swimming events. *International SportMed Journal*, *11*(3), 324-335.

Sánchez, J. A., & Arellano, R. (2002). Stroke index values according to level, gender, swimming style and event race distance. In *ISBS-Conference Proceedings Archive*.

Seifert, L., & Chollet, D. (2005). A new index of flat breaststroke propulsion: A comparison of elite men and women. *Journal of sports sciences*, *23*(3), 309-320.

Seifert, L., Komar, J., Crettenand, F., Dadashi, F., Aminian, K., & Millet, G. P. (2014). Inter-limb coordination and energy cost in swimming. *Journal of science and medicine in sport*, *17*(4), 439-444.

Seifert, L., Leblanc, H., Chollet, D., & Delignières, D. (2010). Inter-limb coordination in swimming: Effect of speed and skill level. *Human movement science*, *29*(1), 103-113.

Seifert, L., Leblanc, H., Herault, R., Komar, J., Button, C., & Chollet, D. (2011). Inter-individual variability in the upper–lower limb breaststroke coordination. *Human movement science*, *30*(3), 550-565.

Sharp, R. L., & Costill, D. L. (1989). Influence of body hair removal on physiological responses during breaststroke swimming. *Medicine and science in sports and exercise*, *21*(5), 576-580.

Soares, P. M., Sousa, F., & Vilas-Boas, J. P. (1999). Differences in breaststroke synchronisation induced by different race velocities. *KL Keskinen, PV Komi, AP Hollander, Swimming science VIII*, 53-57.

Stachowicz, M., & Milde, K. (2023). Changes in thrust force in swimmers in the annual training cycle*. Biomedical human kinetics*, 15(1), 159-171.

Staniak, Z., Buśko, K., Górski, M., & Pastuszak, A. (2016). Accelerometer profile of motion of the pelvic girdle in breaststroke swimming. *Journal of human kinetics*, *52*(1), 147-156.

Stosic, J., Veiga, S., Trinidad, A., Dopsaj, M., & Navarro, E. (2022). Effect of breakout phase on the stroke kinematics and coordinative swimming variables. *Sports biomechanics*, 1-14.

Strzala, M., Krezalek, P., Glab, G., Kaca, M., Ostrowski, A., Stanula, A., & Tyka, A. K. (2013). Intra-cyclic phases of arm-leg movement and index of coordination in relation to sprint breaststroke swimming in young swimmers. *Journal of sports science and medicine*, *12*(4), 690-697.

Strzała, M., Krężąłek, P., Kucia-Czyszczoń, K., Ostrowski, A., Stanula, A., Tyka, A. K., & Sagalara, A. (2014). Coordination and propulsion and non-propulsion phases in 100 meters breaststroke swimming. *Acta of bioengineering and biomechanics*, *16*(4).

Strzala, M., Stanula, A., Głab, G., Glodzik, J., Ostrowski, A., Kaca, M., & Nosiadek, L. (2015). Shaping physiological indices, swimming technique, and their influence on 200m breaststroke race in young swimmers. *Journal of sports science & medicine*, *14*(1), 110.

Strzała, M., Stanula, A., Ostrowski, A., Kaca, M., Krężałek, P., & Głodzik, J. (2016). Propulsive limb coordination and body acceleration in sprint breaststroke swimming. *The journal of sports medicine and physical fitness*, *57*(12), 1564-1571.

Takagi, H., Sugimoto, S., Nishijima, N., & Wilson, B. (2004). Swimming: Differences in stroke phases, arm-leg coordination and velocity fluctuation due to event, gender and performance level in breaststroke. *Sports biomechanics*, *3*(1), 15-27.

Thompson, K. G. (1998). Differences in blood lactate concentrations in national breaststroke swimmers after heats and finals. *Journal of sports sciences*, *16*(1), 63-64.

Thompson, K. G., Haljand, R., & MacLaren, D. P. (2000). An analysis of selected kinematic variables in national and elite male and female 100-m and 200-m breaststroke swimmers. *Journal of sports sciences*, *18*(6), 421-431.

Thompson, K. G., MacLaren, D. P., Lees, A., & Atkinson, G. (2004). The effects of changing pace on metabolism and stroke characteristics during high-speed breaststroke swimming. *Journal of sports sciences*, *22*(2), 149-157.

Thompson, K., MacLaren, D., Lees, A., & Atkinson, G. (2003). The effect of even, positive and negative pacing on metabolic, kinematic and temporal variables during breaststroke swimming. *European journal of applied physiology*, *88*(4), 438-443.

Troup, J. P. (1991). *International center for aquatic research annual: studies by the international center for aquatic research 1990-91*. United States swimming press.

Van Houwelingen, J., Roerdink, M., Huibers, A. V., Evers, L. L., & Beek, P. J. (2017). Pacing the phasing of leg and arm movements in breaststroke swimming to minimize intra-cyclic velocity fluctuations. *PloS one*, *12*(10), e0186160.

Vilas-Boas, J. P. (2005). Speed fluctuations and energy cost of different breaststroke techniques. In *Biomechanics and medicine in swimming VII* (pp. 167-171). Routledge.

Vilas-Boas, J. P. (1994). Maximum propulsive force and maximum propulsive resultant impulse per phase relationships in breaststroke swimming technique. In *ISBS-Conference Proceedings Archive*.

Miyashita, M., Mutoh, Y., Richardson, A. B., & Basel, M. S. S. (1994, November). Comparison of swimming economy in three breaststroke techniques. In *medicine and science in aquatic sports: 10th FINA world sport medicine congress, Kyoto, October 1993* (Vol. 39, pp. 48-54). Karger medical and scientific publishers.

Vorontsov, A. R., & Rumyantsev, V. A. In Zatsiorsky VM (Ed.). (2000). Resistive forces in swimming Resistive forces in swimming (pp. 184–204). *Blackwell science*.

Wettengl, C., Karlsson, R., Olstad, B. H., & Gonjo, T. (2023). Load–velocity profile and active drag in young female swimmers: An Age-Group Comparison. *International journal of sports physiology and performance*, 19(1), 44-52.

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. *Journal of sports sciences*, *25*(4), 375-379.

Zamparo, P. (2006). Effects of age and gender on the propelling efficiency of the arm stroke. *European journal of applied physiology*, 97(1), 52-58.

Zompanakis, I., Papadimitriou, K., Georgios, T., & Dimitrios, L. (2021). The effects of reduced breathing on swimming performance and on blood lactate concentration in 25 and 50 m breaststroke swimming at maximal intensity. *in international conference of sports science- AESA* (No. 4).

Chapter 3

Alves, F., Cunha, P., Gomes-Pereira, J. (1999). Kinematic changes with inspiratory actions in butterfly swimming. In: Keskinen KL, Komi PV, Hollander AP (eds). *Biomechanics and medicine in swimming VIII*. Finland, Jyvaskyla: University of Jyvaskyla. 9-14.

Alves, M., Barbosa, T. M., & Vilas-Boas, J. P. (2024). Exploring the impact of breathing patterns on active drag in breaststroke swimming. *Journal of biomechanics*, 112390.

Barbosa, T. M., Fernandes, R., Keskinen, K. L., Colaço, P., Cardoso, C., Silva, J., &; Vilas-Boas, J. P. (2006). Evaluation of the energy expenditure in competitive swimming strokes. *International journal of sports medicine*, 27(11), 894-899.

Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European journal of applied physiology and occupational physiology*, 78, 385-393.

Carvalho, D. D., Soares, S., Zacca, R., Sousa, J., Marinho, D. A., Silva, A. J., Vilas-Boas, J.P. & Fernandes, R. J. (2020). Anaerobic threshold biophysical characterization of the four swimming techniques. *International journal of sports medicine*, 41(5), 318–327.

Chainok, P., de Jesus, K., Coelho, L., Ayala, H. V. H., de Castro Ribeiro, M. G., Fernandes, R. J., & Vilas-Boas, J. P. (2023). Modeling and predicting the backstroke to breaststroke turns performance in age-group swimmers. *Sports biomechanics*, 22(12), 1700-1721.

Chatard JC, Lavoie JM, Lacour JR (1990) Analysis of determinants of swimming economy in front crawl. *European journal of applied physiology*, 61:88–92

Chollet, D., Seifert, L., Leblanc, H., Boulesteix, L., & Carter, M. (2004). Evaluation of arm-leg coordination in flat breaststroke. *International journal of sports medicine*, 25(07), 486-495.

Counsilman, J. E. (1975). Hypoxic and other methods of training evaluated. *Swimming technique*, 12(1), 19-26.

Dadashi, F., Millet, G., & Aminian, K. (2013). Inertial measurement unit and biomechanical analysis of swimming: an update. *Swiss Society of Sports Medicine*, 61, 21-26.

de Jesus, K., de Jesus, K., Figueiredo, P.A., Gonçalves, P., Vilas-Boas, J.P., Fernandes, R.J. (2012). Effects of fatigue on kinematical parameters during submaximal and maximal 100-m butterfly bouts. *Journal of applied biomechanics, 28: 599-607.*

Di Prampero, P. E., Dekerle, J., Capelli, C., & Zamparo, P. (2008). The critical velocity in swimming. *European journal of applied physiology*, 102(2), 165–171.

Dicker, S. G., Lofthus, G. K., Thornton, N. W., & Brooks, G. A. (1980). Respiratory and heart rate responses to tethered controlled frequency breathing swimming. *Medicine and science in sports and exercise*, *12*(1), 20-23

Fernandes, A.; Costa, M.J.; Mezêncio, B.; Vilas-Boas, J.P.; Fernandes, R.J. (2024). Breaststroke and butterfly intercycle kinematic variation according to different competitive levels with Statistical Parametric Mapping analysis. *Journal of biomechanics*, 176 (112380).

Fernandes, R.J.; Billat, V.L.; Cruz, A.C.; Colaço, P.J.; Cardoso, C.S.; Vilas-Boas, J.P. (2005). Has gender any effect on the relationship between time limit at VO2max velocity and swimming economy? *Journal of human movement studies*, 49: 127-148.

Fernandes, R.J.; de Jesus, K.; Baldari, C.; de Jesus, K.; Sousa, A.C.; Vilas-Boas, J.P.; Guidetti, L. (2012). Different VO2max time-averaging intervals in swimming. *International journal of sports medicine*, 33: 1010-1015.

Fernandes, R; Sousa, M.; Pinheiro, A.; Vilar, S.; Colaço, P.; Vilas-Boas, JP.; (2010). Assessment of individual anaerobic threshold and stroking parameters in swimmers aged 10-11 years. *European Journal of Sport Science*, 10 (5): 311-317.

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European journal of applied physiology*, 111, 767-777.

Figueiredo, P.; Toussaint, H.; Vilas-Boas, J.P.; 2013b Fernandes, R.J. (2013). Relation between efficiency and energy cost with coordination in aquatic locomotion. *European journal of applied physiology*, 113: 651-659.

Gatta, G., Cortesi, M., Fantozzi, S., & Zamparo, P. (2015). Planimetric frontal area in the four swimming strokes: Implications for drag, energetics and speed. *Human movement science*, 39, 41-54.

Gonjo, T.; McCabe, C.; Coleman, S.; Soares, S.; Fernandes, R.J.; Vilas-Boas, J.P.; Sanders, R. (2021). Do swimmers conform to criterion speed during pace-controlled swimming in a 25-m pool using a visual light pacer? *Sports biomechanics*, 20 (6): 651-664.

Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of motor behavior*, 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.

Holfelder, B., Brown, N., Bubeck, D., & Ruiz, J. R. (2013). The influence of sex, stroke and distance on the lactate characteristics in high performance swimming. *PLOS One*, 8(10), e77185.

Hólmer I, Gullstrand L (1980) Physiological responses to swimming with a controlled frequency of breathing. *Scandinavian journal of medicine & science in sports*, 2: 1-6.

Kapus J, Usaj A, Kapus V, Strumbelj B (2003) Influence of reduced breathing during swimming on some respiratory and metabolic values in blood. *Kinesiologia slovenica*, 9: 12-17.

Key, M. A., Eschbach, C. L., & Bunn, J. A. (2014). Assessment of the effects of controlled frequency breathing on lactate levels in swimming. *Journal of athletic enhancement*, *3*, *5*, 2.

Kjendlie PL, Ingjer F, Madsen O, Stallman RK, Stray-Gundersen J (2004) Differences in the energy cost between children and adults during front crawl swimming. *European journal of applied physiology*, 91:473–480

Kjendlie, P. L., & Stallman, R. K. (2008). Drag characteristics of competitive swimming children and adults. *Journal of applied biomechanics*, 24(1), 35-42.

Kolmogorov, S. V., Rumyantseva, O. A., Gordon, B. J., & Cappaert, J. M. (1997). Hydrodynamic characteristics of competitive swimmers of different genders and performance levels. *Journal of applied biomechanics*, 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. *Applied sciences*, 11(18), 8511.

Lavoie, J.M.; Léger, L.A.; Montpetit, R.R. & Chabot, S. (1983). Backward extrapolation of VO2 from the O2 recovery curve after a voluntary maximal 400 m swim. *Biomechanics and medicine in swimming*, 222-227.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic distance per stroke phase, velocity fluctuations and acceleration time ratio of a breaststroker's hip: a comparison between elite and nonelite swimmers at different race paces. *International journal of sports medicine*, 28(02), 140-147.

Lomax, M., Royal, J. T., Kapus, J., Massey, H., & Saynor, Z. (2022). Oxygen uptake kinetics and ventilatory and metabolic parameters do not differ between moderate-intensity front crawl and breaststroke swimming. *Physiological Reports*, 10(12), e15361.

Marinho, D. A., Amorim, R. A., Costa, A. M., Marques, M. C., Pérez-Turpin, J. A., & Neiva, H. P. (2011). “Anaerobic” critical velocity and swimming performance in young swimmers. *Journal of human sport & exercise*, 6(1), 80–86.

Monteiro, A. S., Carvalho, D. D., Azevedo, R., Vilas-Boas, J. P., Zacca, R., & Fernandes, R. J. (2020). Post-swim oxygen consumption: assessment methodologies and kinetics analysis. *Physiological measurement*, 41(10), 105005.

Murlasits, Z., Laszlo, S., Prokai, J., Sebesi, B., Scherer, J., Tovari, F. & Vaczi, M. (2023). Physiological responses to an incremental swim test with different breathing frequencies in competitive male youth swimmers. *Journal of physical education and sport*, 23(3), 697-703

Oxford, S. W., James, R. S., Price, M. J., Payton, C. J., & Duncan, M. J. (2017). Changes in kinematics and arm–leg coordination during a 100-m breaststroke swim. *Journal of sports sciences*, *35*(16), 1658-1665

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, A., Bushnell, D., & Paschke, D. (2005). The influence of drag on human locomotion in water. *Undersea Hyperb Med*, *32*(1), 45-57.

Sanders, R. H. (1995). Can skilled performers readily change technique? An example, conventional to wave action breaststroke. *Human movement science*, 14(6), 665-679.

Seifert, L., & Chollet, D. (2005). A new index of flat breaststroke propulsion: A comparison of elite men and women. *Journal of sports sciences*, *23*(3), 309-320.

Seifert, L., Chollet, D., & Sanders, R. (2010). Does breathing disturb coordination in butterfly?. *International journal of sports medicine*, 31(03), 167-173.

Sousa, A. C., Vilas-Boas, J. P., & Fernandes, R. J. (2014). VO2 kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at VO2 max. *BioMed research international*, *2014*(1), 675363.

Takagi, H., Sugimoto, S., Nishijima, N., & Wilson, B. (2004). Swimming: Differences in stroke phases, arm-leg coordination and velocity fluctuation due to event, gender and performance level in breaststroke. *Sports biomechanics*, *3*(1), 15-27.

Thevelein, X., Daly, D., Persyn, U. (1984) Measurement of total energy use in the evaluation of competitive swimmers. In Bachl, N., Prakop, L., Suckaert, R. (eds.) *Current topics in sports medicine,* pp. 668-676. Urban & Schwartzenberg, Wien.

Troup, J. (1991). Aerobic characteristics of the four competitive strokes. *Annual studies by the international center for aquatic research*, 3-7.

Vilas-Boas, J. P., & Santos, P. J. (1994). Comparison of swimming economy in three breaststroke techniques. In M. Miyashita, M. Mutoh, & A. B. Richardson (Eds.), *Medicine and science in aquatic sports, medicine and sport science* (pp. 48–54). Karger.

Vilas-Boas, J.P., Costa, L., Fernandes, R., Ribeiro, J., Figueiredo, P., Marinho, D., Silva, A., Rouboa, A., Machado, L. (2010). Determination of the drag coefficient during the first and second gliding positions of the breaststroke underwater stroke. *Journal of applied biomechanics*, 26 (3): 324 – 331.

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993). Does critical swimming velocity represent exercise intensity at maximal lactate steady state?. *European journal of applied physiology and occupational physiology*, *66*, 90-95.

West, S. A., Drummond, M. J., VanNess, J. M., & Ciccolella, M. E. (2005). Blood lactate and metabolic responses to controlled frequency breathing during graded swimming. *The journal of strength & conditioning research*, *19*(4), 772-776.

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. *Journal of sports sciences*, 25(4), 375-379.

Zacca, R.; Azevedo, R.; Silveira, R.; Vilas-Boas, J.P.; Pyne, D.B.; de Castro, F.A.S.; Fernandes, R.J. (2019). Comparison of incremental intermittent and time trial testing in age-group swimmers. *The journal of strength & conditioning research*, 33 (3): 801-810.

Zacca, R.; Mezêncio, B.; Castro, F.A.S.; Nakamura, F.Y.; Pyne, D. B.; Vilas-Boas, J. P.; Fernandes, R. J. (2022). Case study: comparison of swimsuits and wetsuits through biomechanics and energetics in elite female open water swimmers. *International journal of sports physiology and performance*, 17: 130-136.

Zompanakis, I., Papadimitriou, K., Georgios, T., & Dimitrios, L. (2021). The effects of reduced breathing on swimming performance and on blood lactate concentration in 25 and 50 m breaststroke swimming at maximal intensity. *in international conference of sports science- AESA* (No. 4).

Chapter 4

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 KL, Komi PV, Hollander AP (eds). *Biomechanics and medicine in swimming VIII*. Finland, Jyvaskyla: University of Jyvaskyla. 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. *Scandinavian journal of medicine & science in 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., and Burkett, B. (2012). Comparative analysis of active drag using the MAD system and an assisted towing method in front crawl swimming. *Journal of applied biomechanics*, 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. *Journal of motor behavior*, 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. *Journal of sports sciences*, 4(1), 21–30.

Kjendlie, P. L., & Stallman, R. K. (2008). Drag characteristics of competitive swimming children and adults. *Journal of applied biomechanics*, 24(1), 35-42.

Kolmogorov, S. V. (2008). Kinematic and dynamic characteristics of steady-state non-stationary motion of elite swimmers. *Russian Journal of biomechanics*, 12(4), 56–70.

Kolmogorov, S. V., & Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of biomechanics*, 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. *Journal of applied biomechanics*, 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. *Applied sciences*, 11(18), 8511.

Kolmogorov, S. (2023). Development of the technology to measure active drag of swimmers by the method of small perturbations. *Journal of biomechanics*, 149, 111486.

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?. *Journal of sports science & medicine*, 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., 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. *Journal of human kinetics*, *86*, 41.

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. *Human movement science*, 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. *Medicine & science in sports & exercise*, 52(11), 2357-2364.

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, A., 2nd, Bushnell, D., and 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 biomechanics*, 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. *The journal of strength & conditioning research,* 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. *Journal of biomechanics*, 21(5), 435-438.

Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of biomechanics*, 37(11), 1655-1663.

Webb, A., Taunton, D. J., Hudson, D. A., Alexander, F., J, 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. *Journal of sports sciences*, 25(4), 375-379.

Zamparo, P., Gatta, G., Pendergast, D., & Capelli, C. (2009). Active and passive drag: the role of trunk incline. *European journal of applied physiology*, 106, 195-205.

Zompanakis, I., Papadimitriou, K., Georgios, T., & Dimitrios, L. (2021). The effects of reduced breathing on swimming performance and on blood lactate concentration in 25 and 50 m breaststroke swimming at maximal intensity. *in international conference of sports science- AESA* (No. 4).

Chapter 5

Alves F, Cunha P, Gomes-Pereira J. Kinematic changes with inspiratory actions in butterfly swimming (1999). In: Keskinen KL, Komi PV, Hollander AP (eds). *Biomechanics and medicine in swimming VIII*. Finland, Jyvaskyla: University of Jyvaskyla; 9 – 14.

Alves, M., Barbosa, T. M., & Vilas-Boas, J. P. (2024). Exploring the impact of breathing patterns on active drag in breaststroke swimming. *Journal of biomechanics*, 177, 112390.

Andersen, J., Sinclair, P., Fernandes, R. J., Vilas-Boas, J. P., & Sanders, R. (2023). Is torso twist production the primary role of the torso muscles in front crawl swimming?. *Sports biomechanics*, 22(12), 1602-1616.

Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. *Journal of science and medicine in sport*, 13(2), 262-269.

Barbosa, T. M., Goh, W. X., Morais, J. E., Costa, M. J., & Pendergast, D. (2016). Comparison of classical kinematics, entropy, and fractal properties as measures of complexity of the motor system in swimming*. Frontiers in psychology*, 7, 1566.

Barbosa, T. M., Lima, F., Portela, A., Novais, D., Machado, L., Colaco, P., Goncalves, R. F., Keskinen, K. L., & Vilas-Boas, J. P. (2006). Relationships between energy cost, swimmming velocity and speed fluctuation in competitive swimming strokes. *Biomechanics and medicine in swimming X*, 6(Suppl2), 192-194.

Barbosa, T. M., Morouço, P. G. F., Jesus, S., Feitosa, W. G., Costa, M. J., Marinho, D. A. & Garrido, N. D. (2013). The interaction between intra-cyclic variation of the velocity and mean swimming velocity in young competitive swimmers. *International journal of sports medicine*, *34*(02), 123-130.

Barbosa, T. M., Simin, C., Forte, P., & Morais, J. E. (2016). The changes in fractal dimension after a maximal exertion in swimming. In *2016 1st international conference on technology and innovation in sports, health and wellbeing (TISHW)* (pp. 1-6). IEEE.

Barbosa, T., Morais, J., Bartolomeu, R., & Costa, M. (2017a). Comparison of fractal dimension among swimmers with different levels of expertise.

Barbosa, T. M., Goh, W. X., Morais, J. E., & Costa, M. J. (2017b). Variation of linear and nonlinear parameters in the swim strokes according to the level of expertise. *Motor control*, 21(3), 312-326.

Bravi, A., Longtin, A., & Seely, A. J. (2011). Review and classification of variability analysis techniques with clinical applications. *Biomedical engineering online*, 10, 1-27.

Cardelli, C., Lerda, R., & Chollet, D. (2000). Analysis of breathing in the crawl as a function of skill and stroke characteristics. *Perceptual and motor skills*, *90*(3), 979-987.

Castiglioni, P., Di Rienzo, M., Parati, G., & Faini, A. (2011). Fractal dimension of mean arterial pressure and heart-rate time series from ambulatory blood pressure monitoring devices. In *2011 Computing in Cardiology* (pp. 593-596). IEEE.

Chatard JC, Padilla S, Cazorla G, Lacour JR (1985) Infuence of body height, weight, hydrostatic lift and training on the energy cost of front crawl. *The New Zealand journal of sports medicine,* 13:82–84

Couto, J. G. M., Franken, M., & Castro, F. A. de S. (2014). Influence of different breathing patterns on front crawl kinematics. *Revista Brasileira de Cineantropometria e Desempenho Humano*, 17(1), 82–90.

De Jesus, K., Sanders, R., De Jesus, K., Ribeiro, J., Figueiredo, P., Vilas-Boas, J. P., & Fernandes, R. J. (2016). The effect of intensity on 3-dimensional kinematics and coordination in front-crawl swimming. *International journal of sports physiology and performance*, 11(6), 768-775.

Den Hartigh, R. J., Cox, R. F., Gernigon, C., Van Yperen, N. W., & Van Geert, P. L. (2015). Pink noise in rowing ergometer performance and the role of skill level. *Motor control*, 19(4), 355-369.

Ferguson, C. J. (2016). An effect size primer: a guide for clinicians and researchers.

Fernandes, A., Costa, M. J., Mezêncio, B., Vilas-Boas, J. P., & Fernandes, R. J. (2024). Breaststroke and butterfly intercycle kinematic variation according to different competitive levels with Statistical Parametric Mapping analysis. *Journal of biomechanics*, 176, 112380.

Fernandes, A., Goethel, M., Marinho, D. A., Mezêncio, B., Vilas-Boas, J. P., & Fernandes, R. J. (2022). Velocity variability and performance in backstroke in elite and good-level swimmers*. International journal of environmental research and public health*, 19(11), 6744.

Figueiredo, P., Kjendlie, P. L., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Intracycle velocity variation of the body centre of mass in front crawl. *International journal of sports medicine*, *33*(04), 285-290.

Figueiredo, P.; Marques, E.A.; Vilas-Boas, J.P.; Fernandes, R.J. Methods of intracycle velocity variation assessment in front crawl. In *Proceedings of the international society of biomechanics*, Natal, Brazil, 4–9 August 2013.

Gonjo, T., Fernandes, R. J., Vilas-Boas, J. P., & Sanders, R. (2023). Is the use of the coefficient of variation a valid way to assess the swimming intra-cycle velocity fluctuation?. *Journal of science and medicine in sport*, *26*(6), 328-334.

Gourgoulis, V., Koulexidis, S., Gketzenis, P., & Tzouras, G. (2018). Intracyclic velocity variation of the center of mass and hip in breaststroke swimming with maximal intensity. *The journal of strength & conditioning research*, *32*(3), 830-840.

Hahn, A., & Krug, T. (2013). Application of knowledge gained from the coordination of partial movements in breaststroke and butterfly swimming for the development of technical training. In *Biomechanics and medicine in swimming V1* (pp. 144-148). Taylor & Francis.

Higuchi, T. (1988). Approach to an irregular time series on the basis of the fractal theory. *Physica D: nonlinear phenomena*, 31(2), 277-283.

Hoos, O., Boeselt, T., Steiner, M., Hottenrott, K., & Beneke, R. (2014). Long-range correlations and complex regulation of pacing in long-distance road racing. *International journal of sports physiology and performance*, 9(3), 544-553.

Kjendlie PL, Ingjer F, Madsen O, Stallman RK, Stray-Gundersen J (2004b) Differences in the energy cost between children and adults during front crawl swimming. *European journal of applied physiology,* 91:473–480

Kjendlie, P. L., & Stallman, R. K. (2008). Drag characteristics of competitive swimming children and adults. *Journal of applied biomechanics*, 24(1), 35-42.

Kjendlie, P. L., Ingjer, F., Stallman, R. K., & Stray-Gundersen, J. (2004a). Factors affecting swimming economy in children and adults. *European journal of applied physiology*, 93, 65-74.

Matsuda, Y., Yamada, Y., Ikuta, Y., Nomura, T., & Oda, S. (2014). Intracyclic velocity variation and arm coordination for different skilled swimmers in the front crawl. *Journal of human kinetics*, 44, 67.

McCabe, C. B., Sanders, R. H., & Psycharakis, S. G. (2015). Upper limb kinematic differences between breathing and non-breathing conditions in front crawl sprint swimming. *Journal of biomechanics*, 48(15), 3995–4001.

Miller, D. I. (1975). Biomechanics of Swimming. *Exercise and sport sciences reviews*, 3(1), 219-248.

Morais, J. E., Barbosa, T. M., Gonjo, T., & Marinho, D. A. (2023). Using Statistical Parametric Mapping as a statistical method for more detailed insights in swimming: a systematic review. *Frontiers in physiology*, 14, 1213151.

Pedersen, T., & Kjendlie, P.-L. (2006). The effect of the breathing action on velocity in front crawl sprinting. *Biomechanics and medicine in swimming X*, (November), 75–77.

Pendergast, D., Mollendorf, J., Zamparo, P., Termin, A., Bushnell, D., & Paschke, D. (2005). The influence of drag on human locomotion in water. *Undersea & hyperbaric medical society*, *32*(1), 45-57.

Persyn, U., Colman, V., & Ungerechts, B. (2005). Diagnosis & advice in the undulating strokes. Coaches' information service-website: http://www. coachesinfo. com (online version 12/02/2007).

Psycharakis, S. G., Naemi, R., Connaboy, C., McCabe, C., & Sanders, R. H. (2010). Three-dimensional analysis of intracycle velocity fluctuations in front crawl swimming. *Scandinavian journal of medicine & science in sports*, 20(1), 128-135.

Qualisys. (2021). Sports marker set. Retrieved from https://cdn-content.qualisys.com/2021/11/Sports-Marker-Set.pdf

Sanders, R. H. (1996). Breaststroke technique variations among New Zealand Pan Pacific squad swimmers. *Biomechanics and medicine in swimming VII*, 64-69.

Schnitzler, C., Seifert, L., Ernwein, V., & Chollet, D. (2008). Arm coordination adaptations assessment in swimming. *International journal of sports medicine*, 29(06), 480-486.

Seifert, L., Chollet, D., & Sanders, R. (2010). Does breathing disturb coordination in butterfly? *International journal of sports medicine*, 31(03), 167-173.

Seifert, L., Komar, J., Crettenand, F., & Millet, G. (2014). Coordination pattern adaptability: energy cost of degenerate behaviors. *PloS one*, 9(9), e107839.

Slopecki, M., Clément, J., Charbonneau, M., & Côté, J. N. (2024). The impact of limb symmetry on stroke-to-stroke movement variability in para-swimmers during an adapted aerobic step test. *ISBS Proceedings Archive*, 42(1), 862.

Roithner, R., Schwameder, H., & Mueller, E. (2000). Determination of optimal filter parameters for filtering kinematic walking data using Butterworth low pass filter. In *ISBS-Conference Proceedings Archive*.

Toussaint HM and Beek PJ (1992) Biomechanics of competitive front crawl swimming. *Sports Medicine*. 13:8-24.

Tucker, R., Bester, A., Lambert, E. V., Noakes, T. D., Vaughan, C. L., & Gibson, A. S. C. (2006). Non-random fluctuations in power output during self-paced exercise. British *Journal of Sports Medicine*, 40(11), 912-917.

Vezos, N., Gourgoulis, V., Aggeloussis, N., Kasimatis, P., Christoforidis, C., & Mavromatis, G. (2007). Underwater stroke kinematics during breathing and breath-holding front crawl swimming. *Journal of sports science & medicine*, *6*(1), 58.

Vieira, L., Soares, S., Costa, M. J., Fernandes, R. J., Ferreira, F. A., Goethel, M., & Vilas-Boas, J. P. (2024). Comparação da velocidade intracíclica de nado obtida por unidade inercial e por velocímetro. *Motricidade*, 20, 1-3.

Vilas-Boas, J. P. (1993). Caracterização biofísica de três variantes da técnica de bruços (Ph.D Thesis, University of Porto). Porto, *Medisa - edições e divulgações científicas*, Lda. (ISBN: 972-8105-02-9)

Vilas-Boas, J. P. (1996). Speed fluctuations and energy cost of different breaststroke techniques. *Biomechanics and medicine in swimming VII*, 7, 167-171.

Vilas-Boas, J. P., Fernandes, R. J., & Barbosa, T. M. (2011). Intra-cycle velocity variations, swimming economy, performance and training in swimming. *The world book of swimming: from science to performance*. New York, NY: Nova Science Publishers, Hauppauge, 119-134.

Witte, K., & Blaser, P. (2001). Importance of the nonlinear time series analysis in sports. In *ISBS-Conference Proceedings Archive*.

Yentes, J. M., Hunt, N., Schmid, K. K., Kaipust, J. P., McGrath, D., & Stergiou, N. (2013). The appropriate use of approximate entropy and sample entropy with short data sets. *Annals of biomedical engineering*, *41*, 349-365.

Zompanakis, I., Papadimitriou, K., Georgios, T., & Dimitrios, L. (2021). The effects of reduced breathing on swimming performance and on blood lactate concentration in 25 and 50 m breaststroke swimming at maximal intensity. *in international conference of sports science- AESA* (No. 4).

Chapter 6

Alexander, R. M. (1977). Swimming. In *Locomotion of Animals* (pp. 13-38). Dordrecht: Springer Netherlands.

Alves, M., Fonseca, P., Fernandes, A., Brito, A. V., Barbosa, T. M., & Vilas-Boas, J. P. (2025). Analyzing breathing patterns in the breaststroke technique through dual-media kinematics and fractal dimension. *Sensors*, 25(10), 3104.

Barbosa, T. M., Fernandes, R., Keskinen, K. L., Colaço, P., Cardoso, C., Silva, J., &; Vilas-Boas, J. P. (2006). Evaluation of the energy expenditure in competitive swimming strokes. *International Journal of Sports Medicine*, 27(11), 894-899.

Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European Journal of Applied Physiology and Occupational Physiology*, 78(5), 385-393.

Carvalho, D. D., Soares, S., Zacca, R., Sousa, J., Marinho, D. A., Silva, A. J., Vilas-Boas, J.P. & Fernandes, R. J. (2020). Anaerobic threshold biophysical characterization of the four swimming techniques. *International Journal of Sports Medicine*, 41(5), 318–327.

Chatard JC, Lavoie JM, Lacour JR (1990) Analysis of determinants of swimming economy in front crawl. *European Journal of Applied Physiology,* 61, 88–92

Chatard JC, Padilla S, Cazorla G, Lacour JR (1985) Influence of body height, weight, hydrostatic lift and training on the energy cost of front crawl. *The New Zealand Journal of Sports Medicine*, 13, 82–84

Clarys, J. P. (1979). Human morphology and hydrodynamics. *Swimming III*, *8*, 3-41.

Cohen, J. (2013). Statistical power analysis for the behavioral sciences. *Routledge*. 2nd ed. Hillsdale, N.J.: L. Erlbaum Associates; 1988: 553-58.

Counsilman, J. (1968). The science of swimming prentice hall*. Englewood Cliffs, New York, USA*.

Counsilman, J. E. (1971). The application of Bernoulli's principle to human propulsion in water. In *Lewillie & Clarys (Eds) Swimming I,* 1, 59-71.

Di Prampero, P. E. (1986). The energy cost of human locomotion on land and in water. *International Journal of Sports Medicine*, 7(02), 55-72.

Di Prampero, P. E., Pendergast, D. R., Wilson, D. W., & Rennie, D. W. (1974). Energetics of swimming in man. *Journal of Applied Physiology*, 37(1), 1-5.

Di Prampero P. E., Pendergast, D,, Zamparo, P. (2011) Swimming economy (energy cost) and efficiency. In: Seifert L, Chollet D, Mujika I (eds) *Word book of swimming: from science to performance*. Nova Science Publisher, New York, pp 297-312.

Fernandes, R.J.; Billat, V.L.; Cruz, A.C.; Colaço, P.J.; Cardoso, C.S.; Vilas-Boas, J.P. (2005). Has gender any effect on the relationship between time limit at VO2max velocity and swimming economy? *Journal of Human Movement Studies*, 49, 127-148.

Fernandes, R.J.; de Jesus, K.; Baldari, C.; de Jesus, K.; Sousa, A.C.; Vilas-Boas, J.P.; Guidetti, L. (2012). Different VO2max time-averaging intervals in swimming. *International Journal of Sports Medicine*, 33, 1010-1015.

Figueiredo P, Seifert L, Vilas-Boas JP, Fernandes RJ. Individual profiles of spatio-temporal coordination in high intensity swimming. *Human Movement Science*. 2012;31(6), 1200-1212

Figueiredo, P.; Toussaint, H.; Vilas-Boas, J.P.; Fernandes, R.J. (2013). Relation between efficiency and energy cost with coordination in aquatic locomotion. *European Journal of Applied Physiology*, 113, 651-659.

Gonjo, T.; McCabe, C.; Coleman, S.; Soares, S.; Fernandes, R.J.; Vilas-Boas, J.P.; Sanders, R. (2021). Do swimmers conform to criterion speed during pace-controlled swimming in a 25-m pool using a visual light pacer? *Sports Biomechanics*, 20 (6), 651-664.

Hay, J. G. (1986). The state of research on the biomechanics of swimming. *Starting, stroking and turning. Biomechanics laboratory, University of Iowa*, 53-76.

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine+ science in sports+ exercise*, 41(1), 3.

Kippenhan, B. C. (2002). Lower-extremity joint angles used during the breaststroke whip kick. In: Proceedings of swim sessions: XIX international symposium on biomechanics in sports. San Francisco; 2001. p. 48–52.

Kjendlie, P. L., & Stallman, R. K. (2008). Drag characteristics of competitive swimming children and adults. *Journal of Applied Biomechanics*, 24(1), 35-42.

Kjendlie, P. L., Ingjer, F., Stallman, R. K., & Stray-Gundersen, J. (2004). Factors affecting swimming economy in children and adults. *European Journal of Applied Physiology*, 93, 65-74.

Kolmogorov, S. V., & Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of Biomechanics*, 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. *Journal of Applied Biomechanics*, 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. *Applied Sciences*, 11(18), 8511.

Komar J, Leprêtre PM, Alberty M, Vantorre J, Fernandes RJ, Hellard P, Chollet D, Seifert L. Effect of increasing energy cost on arm coordination in elite sprint swimmers. *Human Movement Science*. 2012;31(3), 620-629.

Lavoie, J.M., Léger, L.A., Montpetit, R.R. & Chabot, S. (1983). Backward extrapolation of VO2 from the O2 recovery curve after a voluntary maximal 400 m swim. In: Hollander AP, Huijing PA, de Groot G (eds) Biomechanics and medicine in swimming. *Human Kinetics*, Champaign IL, pp 222–227.

Maglischo, E. W. (1982). Swimming faster: a comprehensive guide to the science of swimming. *Mayfield Publishing Company*, Palo Alto, CA.472

Maglischo, E. W. (1993). Swimming Even Faster. *Mayfield*

Martin, R. B., Yeater, R. A., & White, M. K. (1981). A simple analytical model for the crawl stroke. *Journal of Biomechanics*, *14*(8), 539-548.

Mason, B., Patton, S., & Newton, A. (1989). Propulsion in breaststroke swimming. In W.E. Morrison (eds.), *Proceedings of the VII International Symposium on Biomechanics in Sport*. Melbourne, Australia: Footscray Institute of Technology. 257-267

Mezêncio B, Pinho JP, Huebner R, Serrão J, et al. Overall indexes of coordination in front crawl swimming. *Journal of Sports Sciences*. 2020;38(8), 959-967

Monteiro, A. S., Carvalho, D. D., Azevedo, R., Vilas-Boas, J. P., Zacca, R., & Fernandes, R. J. (2020). Post-swim oxygen consumption: assessment methodologies and kinetics analysis. *Physiological Measurement*, 41(10), 105005.

Morouço, P. G., Marinho, D. A., Izquierdo, M., Neiva, H., & Marques, M. C. (2015). Relative contribution of arms and legs in 30 s fully tethered front crawl swimming. *BioMed Research International*, 2015(1), 563206.

Pendergast, D., Mollendorf, J., Zamparo, P., Termin, A., Bushnell, D., & Paschke, D. (2005). The influence of drag on human locomotion in water. *Undersea & Hyperbaric Medical Society*, 32(1), 45-57.

Peterson Silveira, R., Soares, S. M., Zacca, R., Alves, F. B., Fernandes, R. J., Castro, F. A. D. S., & Vilas-Boas, J. P. (2019). A biophysical analysis on the arm stroke efficiency in front crawl swimming: Comparing methods and determining the main performance predictors. *International Journal of Environmental Research and Public Health*, *16*(23), 4715.

Psycharakis, S. G., & McCabe, C. (2011). Shoulder and hip roll differences between breathing and non-breathing conditions in front crawl swimming. *Journal of Biomechanics*, 44(9), 1752-1756.

Qualisys (2021). Sports marker set. Retrieved in June 2022 from https://cdn-content.qualisys.com/2021/11/Sports-Marker-Set.pdf

Ribeiro J, Figueiredo P, Morais S, Alves F, Toussaint H, Vilas-Boas JP, Fernandes RJ. Biomechanics, energetics and coordination during extreme swimming intensity: effect of performance level. *Journal of Sports Sciences*. 2017;35(12), 1234-1243

Schleihauf, R. E. (1976). A hydrodynamic analysis of breaststroke pulling proficiency. *Swimming Technique*, 12(1), 100-105.

Schleihauf, R. E. (1979). A hydrodynamic analysis of swimming propulsion. In *Swimming III*; Terauds, J., Bedingfield, E.W., Eds.; University Park Press: Baltimore, MA, USA. 70-109.

Shahbazi-Moghadam, M. (2008). Determination of arms and legs contribution to propulsion and percentage of coordination in breaststroke swim. In *ISBS-Conference Proceedings Archive*. 1, p. 58-61.

Sousa, C.A., Vilas-Boas, J.P., Fernandes, R.J. (2014). VO2 kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at VO2max. *BioMed Research International*: 1-9, 675363

Thevelein, X., Daly, D., Persyn, U. (1984) Measurement of total energy use in the evaluation of competitive swimmers. In Bachl, N., Prakop, L., Suckaert, R. (eds.) *Current Topics in Sports Medicine,* pp. 668-676. Urban & Schwartzenberg, Wien. pp 668–676

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. *The Journal of Strength & Conditioning Research*, 25(1), 109-116.

Toussaint, H. M., Beelen, A. N. I. T. A., Rodenburg, A. N. N. E., Sargeant, A. J., de Groot, G. E. R. T., Hollander, A. P., & van Ingen Schenau, G. J. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6), 2506-2512.

Toussaint, H. M., Hollander, A. P., Van den Berg, C., & Vorontsov, A. (2000). Biomechanics of swimming. *Exercise and sport science*, 639-660.

Toussaint, H. M., Janssen, T., & Kluft, M. (1989). The influence of paddles on propulsion. *Swimming Technique*, *26*(2), 28-32.

Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of Biomechanics*, 37(11), 1655-1663.

Vilas-Boas, J. P. (1993). Caracterização biofísica de três variantes da técnica de bruços (Ph.D Thesis, University of Porto). Porto, *Medisa - edições e divulgações científicas*, Lda. (ISBN: 972-8105-02-9)

Vilas-Boas, J. P. (2000). Aproximação biofísica ao desempenho e ao treino de nadadores. *Revista Paulista de Educação Física*, 14(2), 107-117.

Vilas-Boas, J. P., & Santos, P. J. (1994). Comparison of swimming economy in three breaststroke techniques. In M. Miyashita, M. Mutoh, & A. B. Richardson (Eds.), *Medicine and Science in Aquatic Sports, Medicine and Sport Science* (pp. 48–54). Karger.

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. *Journal of Sports Sciences*, 25(4), 375-379.

Zacca, R.; Azevedo, R.; Silveira, R.; Vilas-Boas, J.P.; Pyne, D.B.; de Castro, F.A.S.; Fernandes, R.J. (2019). Comparison of incremental intermittent and time trial testing in age-group swimmers. *The Journal of Strength & Conditioning Research*, 33 (3), 801-810.

Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A., & Minetti, A. E. (2005). An energy balance of front crawl. *European Journal of Applied Physiology*, 94, 134-144.

Zamparo, P.; Turri, E.; Peterson Silveira, R.; Poli, A (2014). The interplay between arms-only propelling efficiency, power output and speed in master swimmers. *European Journal of Applied Physiology,* 114, 1259–1268.

Chapter 7

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, M., Barbosa, T. M., & Vilas-Boas, J. P. (2024). Exploring the impact of breathing patterns on active drag in breaststroke swimming. *Journal of biomechanics*, 177, 112390.

Barbosa, T. M., Goh, W. X., Morais, J. E., & Costa, M. J. (2017b). Variation of linear and nonlinear parameters in the swim strokes according to the level of expertise. *Motor control*, 21(3), 312-326.

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. *Scandinavian journal of medicine & science in sports*, 25(2), e184-e196.

Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European journal of applied physiology and occupational physiology*, 78, 385-393.

Carvalho, D. D., Soares, S., Zacca, R., Sousa, J., Marinho, D. A., Silva, A. J., ... & Fernandes, R. J. (2020). Anaerobic threshold biophysical characterization of the four swimming techniques. *International journal of sports medicine*, *41*(05), 318-327.

Chatard JC, Lavoie JM, Lacour JR (1990) Analysis of determinants of swimming economy in front crawl. *European journal of applied physiology,* 61:88–92

Chatard JC, Padilla S, Cazorla G, Lacour JR (1985) Influence of body height, weight, hydrostatic lift and training on the energy cost of front crawl. *The New Zealand journal of sports medicine*, 13:82–84

Chollet, D., Seifert, L., Leblanc, H., Boulesteix, L., & Carter, M. (2004). Evaluation of arm-leg coordination in flat breaststroke. *International journal of sports medicine*, 25(07), 486-495.

Counsilman, J. (1968). The Science of Swimming Prentice Hall. *Englewood Cliffs, New york*.

Counsilman, J. E. (1969). The role of sculling movements in the arm pull. *Swimming world*, 10(12), 6-7.

Counsilman, J. E. (1971). The application of Bernoulli's principle to human propulsion in water. In *Lewillie & Clarys (Eds) Swimming I,* 1, 59-71.

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.

Dadashi, F., Millet, G., & Aminian, K. (2013). Inertial measurement unit and biomechanical analysis of swimming: an update. *Swiss Society of Sports Medicine*, 61, 21-26.

Di Prampero, P. E., Dekerle, J., Capelli, C., & Zamparo, P. (2008). The critical velocity in swimming. *European journal of applied physiology*, *102*(2), 165-171.

Fernandes, R.J.; Billat, V.L.; Cruz, A.C.; Colaço, P.J.; Cardoso, C.S.; Vilas-Boas, J.P. (2005). Has gender any effect on the relationship between time limit at VO2max velocity and swimming economy? *Journal of human movement studies*, 49: 127-148.

Fernandes, R; Sousa, M.; Pinheiro, A.; Vilar, S.; Colaço, P.; Vilas-Boas, JP.; (2010). Assessment of individual anaerobic threshold and stroking parameters in swimmers aged 10-11 years. Eur J Sport Sci, 10 (5): 311-317.

Figueiredo, P.; Toussaint, H.; Vilas-Boas, J.P.; 2013b Fernandes, R.J. (2013). Relation between efficiency and energy cost with coordination in aquatic locomotion. *European journal of applied physiology*, 113: 651-659.

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

Hay, J. G. (1986). The state of research on the biomechanics of swimming. *Starting, stroking and turning. Biomechanics laboratory, University of Iowa*, 53-76.

Holfelder, B., Brown, N., & Bubeck, D. (2013). The influence of sex, stroke and distance on the lactate characteristics in high performance swimming. *PloS one*, *8*(10), e77185.

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. *Journal of sports sciences*, 4(1), 21–30.

Hólmer I, Gullstrand L (1980) Physiological responses to swimming with a controlled frequency of breathing. *Scandinavian journal of medicine & science in sports*, 2: 1-6.

Kapus J, Usaj A, Kapus V, Strumbelj B (2003) Influence of reduced breathing during swimming on some respiratory and metabolic values in blood*. Kinesiologia slovenica*, 9: 12-17.

Key, M. A., Eschbach, C. L., & Bunn, J. A. (2014). Assessment of the effects of controlled frequency breathing on lactate levels in swimming. *Journal of athletic enhancement*, *3*, *5*, 2.

Kierans, S. J., & Taylor, C. T. (2021). Regulation of glycolysis by the hypoxia-inducible factor (HIF): implications for cellular physiology. *The Journal of physiology*, 599(1), 23-37.

Kjendlie PL, Ingjer F, Madsen O, Stallman RK, Stray-Gundersen J (2004b). Differences in the energy cost between children and adults during front crawl swimming. *European journal of applied physiology,* 91:473–480

Kjendlie, P. L., & Stallman, R. K. (2008). Drag characteristics of competitive swimming children and adults. *Journal of applied biomechanics*, 24(1), 35-42.

Kjendlie, P. L., Ingjer, F., Stallman, R. K., & Stray-Gundersen, J. (2004a). Factors affecting swimming economy in children and adults. *European journal of applied physiology*, 93, 65-74.

Kolmogorov, S. (2023). Development of the technology to measure active drag of swimmers by the method of small perturbations. *Journal of biomechanics*, 149, 111486.

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. *Applied sciences*, 11(18), 8511.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic distance per stroke phase, velocity fluctuations and acceleration time ratio of a breaststroker's hip: a comparison between elite and nonelite swimmers at different race paces. *International journal of sports medicine*, 28(02), 140-147.

Lomax, M., Royal, J. T., Kapus, J., Massey, H., & Saynor, Z. (2022). Oxygen uptake kinetics and ventilatory and metabolic parameters do not differ between moderate-intensity front crawl and breaststroke swimming. *Physiological reports*, *10*(12), e15361.

Maglischo, E. W. (1982). Swimming faster: a comprehensive guide to the science of swimming. *Mayfield publishing company*, Palo Alto.

Marinho, D. A., Amorim, R. A., Costa, A. M., Marques, M. C., Pérez-Turpin, J. A., & Neiva, H. P. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *Journal of human sport and exercise*, *6*(1), 80-86.

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?. *Journal of sports science & medicine*, 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*.

Morouço, P. G., Marinho, D. A., Izquierdo, M., Neiva, H., & Marques, M. C. (2015). Relative contribution of arms and legs in 30 s fully tethered front crawl swimming. *BioMed research international*, 2015(1), 563206.

Murlasits, Z., Laszlo, S., Prokai, J., Sebesi, B., Scherer, J., Tovari, F., ... & Vaczi, M. (2023). Physiological responses to an incremental swim test with different breathing frequencies in competitive male youth swimmers. *Journal of physical education and sport*, 23(3), 697-703

Oxford, S. W., James, R. S., Price, M. J., Payton, C. J., & Duncan, M. J. (2017). Changes in kinematics and arm–leg coordination during a 100-m breaststroke swim. *Journal of sports sciences*, *35*(16), 1658-1665

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.

Persyn, U., Colman, V., & Ungerechts, B. (2005). Diagnosis & advice in the undulating strokes. *Coaches' Information Service-website*: http://www. coachesinfo. com (online version 12/02/2007).

Persyn U., Colman V., Van Tilborgh L. (1992). Movement analysis of the flat and undulating breaststroke pattern. In D. MacLaren, T. Reilly, A. Less (Eds), *Swimming Science VI*, London, E & FN SPON, 75-80

Psycharakis, S. G., Naemi, R., Connaboy, C., McCabe, C., & Sanders, R. H. (2010). Three-dimensional analysis of intracycle velocity fluctuations in frontcrawl swimming. *Scandinavian journal of medicine & science in sports*, 20(1), 128-135.

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 biomechanics*, 1-18.

Sanders, R. H. (1996). Breaststroke technique variations among New Zealand Pan Pacific squad swimmers. *Biomechanics and medicine in swimming VII*, 64-69.

Schleihauf, R. E. (1974). A biomechanical analysis of freestyle. *Swimming technique*, 11(3), 89-96.

Schleihauf, R. E. (1976). A hydrodynamic analysis of breaststroke pulling proficiency. *Swimming technique*, 12(1), 100-105.

Schleihauf, R. E. (1979). A hydrodynamic analysis of swimming propulsion. *Swimming*, 70-109.

Seifert, L., & Chollet, D. (2005). A new index of flat breaststroke propulsion: A comparison of elite men and women. *Journal of sports sciences*, *23*(3), 309-320.

Seifert, L., Komar, J., Crettenand, F., & Millet, G. (2014). Coordination pattern adaptability: energy cost of degenerate behaviors. *PloS one*, 9(9), e107839.

Shahbazi-Moghadam, M. (2008). Determination of arms and legs contribution to propulsion and percentage of coordination in breaststroke swim. In *ISBS-conference proceedings archive*.

Takagi, H., Sugimoto, S., Nishijima, N., & Wilson, B. (2004). Swimming: Differences in stroke phases, arm-leg coordination and velocity fluctuation due to event, gender and performance level in breaststroke. *Sports biomechanics*, *3*(1), 15-27.

Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of biomechanics*, 37(11), 1655-1663.

Vilas-Boas, J. P. (1993). Caracterização biofísica de três variantes da técnica de bruços (Ph.D Thesis, University of Porto). Porto, *Medisa - edições e divulgações científicas*, Lda. (ISBN: 972-8105-02-9)

Vilas-Boas, J. P., & Santos, P. J. (1994). Comparison of swimming economy in three breaststroke techniques. In M. Miyashita, M. Mutoh, & A. B. Richardson (Eds.), *Medicine and science in aquatic sports, medicine and sport science* (pp. 48–54). Karger.

Webb, A., Taunton, D. J., Hudson, D. A., Alexander, F., J, 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.

West, S. A., Drummond, M. J., VanNess, J. M., & Ciccolella, M. E. (2005). Blood lactate and metabolic responses to controlled frequency breathing during graded swimming. *The journal of strength & conditioning research*, *19*(4), 772-776.

Zacca, R.; Mezêncio, B.; Castro, F.A.S.; Nakamura, F.Y.; Pyne, D. B.; Vilas-Boas, J. P.; Fernandes, R. J. (2022). Case study: comparison of swimsuits and wetsuits through biomechanics and energetics in elite female open water swimmers. *International journal of sports physiology and performance,* 17: 130-136.

Zompanakis, I., Papadimitriou, K., Georgios, T., & Dimitrios, L. (2021). The effects of reduced breathing on swimming performance and on blood lactate concentration in 25 and 50 m breaststroke swimming at maximal intensity. *In international conference of sports science- AESA* (No. 4).