Swimming hydrodynamics
New insights about drag and propulsion and their interaction into performance

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List of Publications

This Doctoral Thesis was supported by the research articles shown in Table 1.

Table 1. Identification of peer reviewed articles, indexing and metrics for the doctoral thesis.

Year	Reference	**IF JCR**
2022	Lopes, T. J., Morais, J. E., Pinto, M. P., & Marinho, D. A. (2022). Numerical and experimental methods used to evaluate active drag in swimming: A systematic narrative review. *Frontiers in Physiology*, 13, 938658. doi:10.3389/fphys.2022.938658	4.755
2023	Lopes, T. J., Sampaio, T., Oliveira, J. P., Pinto, M. P., Marinho, D. A., & Morais, J. E. (2023). Using Wearables to Monitor Swimmers' Propulsive Force to Get Real-Time Feedback and Understand Its Relationship to Swimming Velocity. *Applied Sciences*, 13(6), 4027.	2.838
UR	Lopes, T. J., Sampaio, T., Pinto, M. P., Oliveira, J. P., Marinho, D. A., & Morais, J. E. (under review). Comparison of the active drag and passive drag coefficients at the same swimming speed through experimental methods. *European Journal of Human Movement*.	1.681

IF - impact factor; JCR - journal citation reports; UR - under review.

Table 2 presents the preliminary studies according to the type of scientific dissemination.

Table 2. Identification of peer reviewed abstracts for scientific events.

Year	Reference	**Type**
2022	Lopes, T. J., Pinto, M. P., Marinho, D. A., & Morais, J. E. (2023). Numerical and experimental methods used to evaluate active drag parameters in swimming. Seminário Desporto e Ciência 2023. University of Madeira, Portugal.	OC
2023	Lopes, T. J., Morais, J. E., Pinto, M. P., & Marinho, D. A. (2023). Numerical methods used to assess active drag in swimming over the years. Cidesd International Congress 2023. University of Trás-os-Montes and Alto Douro, Portugal.	PC

OC - oral communication; K - keynote; PC - poster communication.

Table 3 presents other studies and research articles carried out during the research period of this thesis, according to the type of scientific dissemination.

Table 3. Identification of peer reviewed articles, indexing and metrics.

Year	Reference	**IF JCR**
2019	Lopes, T. J., Gonçalves, C. A., Graça, C., Neiva, H. P., & Marinho, D. A.* (2019). The Relationship between Front Crawl Swimming Performance and Strength Variables in College Swimmers. *Ergonomics International Journal*, 3(1). doi:10.23880/eoij-16000198	1.9568
2021	Lopes, T. J., Neiva, H. P., Gonçalves, C. A., Nunes, C., & Marinho, D. A. (2021). The effects of dry-land strength training on competitive sprinter swimmers. *Journal of Exercise Science & Fitness*, *19*(1), 32-39. doi:10.1016/j.jesf.2020.06.005	3.682

2022	Morais, J. E., Barbosa, T. M., Lopes, T., Simbaña-Escobar, D., & Marinho, D. A. (2022). Race analysis of the men's 50 m events at the 2021 LEN European Championships. *Sports Biomechanics*, 1-17. doi:10.1080/14763141.2022.2125430	2.279
2022	Morais, J. E., Marinho, D. A., Oliveira, J. P., Sampaio, T., Lopes, T. J., & Barbosa, T. M. (2022). Using statistical parametric mapping to compare the propulsion of age-group swimmers in front crawl acquired with the aquanex system. *Sensors*, 22(21), 8549. doi:10.3390/s22218549	3.847
2022	Morais, J. E., Barbosa, T. M., Lopes, T., & Marinho, D. A. (2022). Race level comparison and variability analysis of 100 m freestyle sprinters competing in the 2019 European championships. *International Journal of Performance Analysis in Sport*, 22(3), 303-316. doi:10.1080/14763141.2022.2125430	2.488
2022	Marinho, D. A., Barbosa, T. M., Auvinen, A., Lopes, T., Silva, A. J., & Morais, J. E. (2022). Smartpaddle as a New Tool for Monitoring Swimmers' Kinematic and Kinetic Variables in Real Time. *The Open Sports Sciences Journal*, *15*(1). doi:10.2174/1875399X-v15-e221026-2022-11	0.741
2023	Morais, J. E., Barbosa, T. M., Lopes, T., Gourgoulis, V., Nikodelis, T., & Marinho, D. A. (2023). Analysis of upper limb propulsion in young swimmers in front-crawl through Statistical Parametric Mapping. *Journal of Biomechanics*, *159*, 111792. doi:10.1016/j.jbiomech.2023.111792	2.640
2023	Morais, J. E., Barbosa, T. M., Lopes, T., Moriyama, S. I., & Marinho, D. A. (2023). Comparison of swimming velocity between age-group swimmers through discrete variables and continuous variables by Statistical Parametric Mapping. *Sports Biomechanics*, 1-12. doi: 10.1080/14763141.2023.2241845	2.279

IF - impact factor; JCR - journal citation reports; UR - under review. * - other corresponding author

Abstract

In Swimming, there are numerous factors that influence performance, where hydrodynamic effects play a key-role. Hydrodynamics in swimming include resistance forces (drag) and propulsive forces. Due to all its complexity, hydrodynamics is one of the most studied areas in swimming. Drag has been extensively studied in swimming. Therefore, the first objective was to better understand how resistive forces are measured with a focus on active drag since swimmers spend of the race swimming. There are experimental and numerical methods to measure or estimate drag. Of all the existing methods for measuring drag, there is no gold standard. Indeed, all studies that compared methods reached the same conclusion: they all measure the same phenomenon despite differences among them. This may occur due to the characteristics of each method. A secondary objective was to use an equipment that collects propulsive data and understand the relationship of propulsive force with other swimming determinants. This is an equipment that is simple to use and understand, with the possibility of being used in a training context. It consists in a wireless sensor that also provides the trajectory of the hand. This way, it was possible to understand at what point of the arm-pull swimmers generate greater forces. All this information is acquired in real time through a mobile application that transmits the swimmers' outputs. In this study, swimming speed, propulsive force and other kinematic and kinetic variables did not change significantly ($p < 0.05$) between sections (only the intracyclic fluctuation of swimming speed decreased significantly, $p = 0.005$). Realizing that swimming speed was determined by the interaction of kinematic and kinetic variables, specifically by propulsive force and active drag coefficient. The third objective was to understand and explain the relevance of using the drag coefficient in hydrodynamic studies. Seeking to improve the efficiency and performance of swimmers, allowing the identification of areas for improvement in swimming technique and the development of more effective training strategies. The drag coefficient can be calculated based on the value of force, obtained by both drag and propulsion, providing a crucial measure to understand and optimize the interaction between the swimmer and the water during swimming. It is possible to see that swimmers have a greater active drag coefficient than the passive one, but with a strong agreement between them. Greater active than passive drag can probably be due to the larger frontal surface area during active conditions. Active coefficient data appears to be a more absolute indicator of drag for determining a hydrodynamic profile. Better than studying isolated cases of propulsion or drag.

Keywords

Resistive forces; propulsive forces; displacement; biomechanics, front crawl; swimming; experimental methods; numerical methods

Resumo

Na Natação existem inúmeros fatores que influenciam o desempenho, onde os efeitos hidrodinâmicos desempenham um papel fundamental. A hidrodinâmica na natação inclui forças de resistência (arrasto) e forças propulsivas. Apesar de toda a sua complexidade, a hidrodinâmica é uma das áreas mais estudadas na natação. O arrasto foi extensivamente estudado na natação. Portanto, o primeiro objetivo foi entender melhor como as forças resistivas são medidas com foco no arrasto ativo, uma vez que os nadadores passam a maior parte da prova a nadar. Existem métodos experimentais e numéricos para medir ou estimar o arrasto. De todos os métodos existentes para medir o arrasto, não existe um *gold-standard*. Na verdade, todos os estudos que compararam métodos chegaram à mesma conclusão: todos medem o mesmo fenómeno, apesar das diferenças entre eles. Isso pode ocorrer devido às características de cada método. Um objetivo secundário foi utilizar um equipamento que coletasse dados propulsivos e entendesse a relação da força propulsiva com outros determinantes da natação. Trata-se de um equipamento de simples utilização e compreensão, com possibilidade de utilização em contexto de treino. Consiste num sensor sem fios que também fornece a trajetória da mão. Dessa forma, foi possível entender em que ponto da puxada de braço (braçada) os nadadores geram maiores forças. Toda esta informação é adquirida em tempo real através de uma aplicação móvel que transmite os resultados dos nadadores. Neste estudo, a velocidade de nado, a força propulsiva e outras variáveis cinemáticas e cinéticas não se alteraram significativamente ($p < 0,05$) entre as seções (apenas a flutuação intracíclica da velocidade de nado diminuiu significativamente, $p = 0,005$). Percebendo que a velocidade da natação foi determinada pela interação de variáveis cinemáticas e cinéticas, especificamente pela força propulsiva e coeficiente de arrasto ativo. O terceiro objetivo foi compreender e explicar a relevância da utilização do coeficiente de arrasto em estudos hidrodinâmicos. De forma a melhorar a eficiência e o desempenho dos nadadores, permitindo a identificação de áreas de melhoria na técnica de natação e o desenvolvimento de estratégias de treino mais eficazes. O coeficiente de arrasto pode ser calculado com base no valor da força, obtido tanto pelo arrasto quanto pela propulsão, fornecendo uma medida crucial para compreender e otimizar a interação entre o nadador e a água durante a natação. É possível perceber que os nadadores possuem um coeficiente de arrasto ativo maior que o passivo, mas com forte concordância entre eles. Um maior arrasto ativo do que passivo provavelmente pode ser devido à maior área de superfície frontal durante condições ativas. Os dados do coeficiente ativo parecem ser um indicador mais absoluto de arrasto para determinar um perfil hidrodinâmico. Melhor do que estudar casos isolados de propulsão ou arrasto.

Palavras-chave

Forças resistivas; forças propulsivas; deslocamento; biomecânica, crol; natação; métodos experimentais; métodos numéricos

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Appendix II

List of abbreviations

ATM	Assisted towing method
AP	Pitch angle
AS	Arm span
BM	Body mass
CFD	Computational fluid dynamics
C_D	Coefficient of drag
C_{DA}	Coefficient of active drag
C_{DP}	Coefficient of passive drag
C_x	Hydrodynamic coefficient
CV	Coefficient of variation
d	Cohen’s effect size
D_A	Active drag
D_P	Passive drag
dv	Speed fluctuation
F_d	Drag Force
F_{mean_right}	Right mean propulsion
F_{mean_left}	Left mean propulsion
F_p	Propulsive force
F_r	Froude number
FSA	Frontal surface area
FSA_{active}	Frontal surface area measure while swimming
$FSA_{passive}$	Frontal surface area while towed
H	Height
HLM	Hierarchical linear modeling
HSA	Hand surface area
ICC	Intra-class correlation coefficients
IdC	Index of coordination
IMU’s	Inertial measurement units
Imp	Impulse
IVV	Intra-cyclic velocity variations
K	Specific constant
MAD	Measuring active drag
MD	Mean difference
MRT	Residual thrust measured values
P	Required power
p	Water density
P_{ai}	Metabolic power (power input);
P_k	Mechanical power to transfer
R^2	Coefficient of determination
SC	Stroke cycle
SD	One standard deviation
SE	Stroke efficiency
SEE	Standard error of estimation
SF	Stroke frequency

SI	Stroke index
SL	Stroke length
SPH	Coupled biomechanical-smoothed particle hydrodynamics
TDI	Technique drag index
TDI_D	Technique drag index considering drag
TDI_{CD}	Technique drag index considering the drag coefficient
TTSA	Trunk transverse surface area
v/V	Swimming speed (velocity)
VPM	Speed perturbation method
WS	Whole stroke
95CI	95% confidence intervals
95PI	95% prediction intervals
$\triangle$	Time the propulsive force was generated

Chapter 1. General Introduction

General information about swimming as a sport and as a holistic phenomenon

Swimming is a cyclic sport that takes place directly in the water. Being performed in the aquatic environment, it ends up being of great interest for researchers as the learning and improving processes are more complex, especially when the competitive level is higher (Toussaint et al., 2004). Competitive swimming from childhood to adulthood aims to cover a certain distance in the shortest time (Costa et al., 2012). Therefore, researchers, coaches, and swimmers must understand how these last ones must improve to deliver the best performances.

More than ever, swimming is considered a holistic phenomenon based on the interaction of several determinants (Barbosa et al., 2010b; Thompson et al., 2000; Santos et al., 2022b). Still, even knowing that most of the priority components in this sport come from biomechanical and physiological processes, they end up failing in the sense that they are not practical for coaches/researchers to use this practice in an efficient and more recurrent way during the sports season (Harden et al., 2020; Lopes et al., 2021; Seifert et al., 2014; Troup, 1999). It is necessary to transmit knowledge and scientific evolution to everyone involved in this sport, but more importantly, to transmit how it can be applicable and in what way (Costa et al., 2015; Harden et al., 2020; Marinho et al., 2022).

Furthermore, as previously mentioned, swimming depends on the interaction of biomechanical, physiological, motor control, strength, conditioning factors, etc. (Amaro et al., 2019; Neiva et al., 2017; Ruiz-Navarro et al., 2022; Silva et al., 2022). It is also important to consider other factors such as mental health (Salehi et al., 2022; Zhang & Liu, 2024), nutrition and recovery (Holway & Spriet, 2011; Pyne et al., 2014), and race strategy (Aspenes & Karlsen, 2012; Morais et al., 2012; Morais et al., 2022a; Vilas-Boas, 2023). Indeed, these factors may play a crucial role in long-term performance (Pyne et al., 2014). It is a complex combination of different elements that contribute to swimming success (Barbosa et al., 2013a; Barbosa et al., 2013b; Morais et al., 2022a). No less important, physiological factors are related to the body's responses during exercise, such as the functioning of the cardiovascular, respiratory, and metabolic systems (Neptune et al., 2009; Psycharakis et al., 2008; Zamparo et al., 2012). Understanding these factors helps swimmers improving their endurance, anaerobic capacity, and recovery ability. Motor control explores the swimmer's ability to coordinate and control muscle movements efficiently to perform the swimming technique correctly (Bogdanoviča & Lāriņš, 2020; Latash & Levin, 2017). This involves integration between the central nervous system and the musculoskeletal system (Latash & Levin, 2017). Finally, strength and conditioning involve physical training outside the water to develop muscular strength, endurance, flexibility, and stability (Lopes et al., 2021; Morais et al., 2018; Wirth et al., 2022). This includes weight-bearing exercises, resistance training, stretching, and specific exercises to strengthen the muscles used in swimming (Lopes et al., 2021; Lum et al., 2019; Morais et al., 2018). Despite all previous assumptions, biomechanics is fundamental in competitive swimming as it offers a detailed understanding of swimming technique, allowing swimmers to optimize their efficiency and performance in the water through precise analysis of movement and force (Troup, 1999; Toussaint et al., 2004). By investigating biomechanical principles, swimming coaches and practitioners can improve swimmers' technique, reduce the risk of injury, and maximize the swimming speed and effectiveness of stroke cycles. Indeed, and based on a biomechanical perspective, swimmers can maximize speed by reducing resistance and maximizing propulsion (Fernandes et al., 2022; Lopes et al., 2022; Morais et al., 2021a).

As previously mentioned, it is fair to say that as this is a sport practiced in water (aquatic/liquid environment), within the biomechanical scientific field, hydrodynamics is highly studied by researchers. The ability of swimmers to move in the water depends on the amount of force applied to the water and the drag forces opposing forward movement (Barbosa et al., 2020). Therefore, deeper knowledge and understanding of deterministic models that bring together an interdisciplinary approach should be considered. The initial model proposed for competitive swimming (Barbosa, et al., 2010a; Barbosa et al., 2013b) highlights an interaction between anthropometry, kinematics, resistance, dry-land conditioning, and water kinetics and how these connections would influence energetics and then swimming performance (Lopes et al., 2021).

Swimming propulsion

Regarding propulsive forces, these are the ones responsible for propelling the swimmer forward in the water (Mullen, 2018; Toussaint & Beek, 1992). They are generated mainly by the action of the upper and lower limbs against the water during the different phases of the stroke and kick cycle (Santos et al., 2021; Soh & Sanders, 2019). A study conducted by Wei et al. (2014), described that regardless of the stroke, the pull or traction refers to the part of the movement of the arm from the head towards the feet, being associated with propulsion. The catch is the initial part of the pull during which the swimmer prepares the arms and body to develop maximum momentum as quickly as possible. Coaches and practitioners often describe this to swimmers in terms of trying to catch as much water with their arms and pushing it back toward their feet. The movement in which the hand advances from the hip to the start of the next pull (i.e., in front of the head) is the recovery (Mullen, 2018; Wei et al., 2014). When it comes to freestyle, better known as the front crawl technique, particularly in the last 20 years there has been a lot of emphasis on high elbows, known as: the recovery phase of the freestyle stroke. The goal is to point the forearms directly toward the bottom of the pool so that throughout the pull, the swimmer engages as much water as possible. In visual and practical terms, as we can see in figure 1, the arm movement towards the feet during the pull creates a drag force on the arm that is a forward propulsive force for the swimmer (Wei et al., 2014). Propulsive forces are maximized when the swimmer performs an efficient swimming technique, using an appropriate combination of strength, speed and coordination to push the water backward and propel the body forward (Morais et al., 2022b; Sanders et al., 2012; Santos et al., 2021; van Houwelingen et al., 2017). The justification for high elbows is to position as much of the arm as possible in an orientation that maximizes the drag coefficient (C_D), as far forward as physiologically possible, and maintain that position for as long as possible during the pull. As shown in figure 1, the concept of high elbows during the pull-up has been at the center of both the technical development and science of competitive swimming (Bilinauskaite et al., 2013; Wei et al., 2014).

Von Loebbecke & Mittal (2012) revisited the problem of calculating the flow around the arm and hand using an immersed boundary method based on finite differences. This technique was described in detail by Mittal et al. (2006). By comparing detailed flow information obtained from their calculations with videos and corresponding swimming speeds of elite swimmers, von Loebbecke & Mittal (2012) came to an interesting conclusion. They discovered that the concept of hydrodynamic lift, introduced by Counsilman (1968, 1971), was an important part of propulsion in freestyle (front crawl) and backstroke. They noted, however, that "exaggerated paddling movements," presumably the S-stroke, reduced net thrust.

Therefore, it is important to state that for all four swimming techniques in swimming, the propulsive force generated by the arms is dominated by the abrupt body drag. It is the swimmer's responsibility, therefore, to wrap as much of the arm perpendicular to the swimming direction (i.e., pointed straight down to the bottom of the pool) as early in the stroke as possible. This is the principle underlying the concept of high elbows (van Houwelingen et al., 2017; Wei et al., 2014).

Furthermore, weight and buoyancy forces are crucial elements in the context of fluid mechanics and play a fundamental role in various aquatic activities, including swimming (Mullen, 2018; van Houwelingen et al., 2017). The force caused by the weight acts on an object in the water due to gravity, determining its tendency to sink or not. On the other hand, the buoyant force, resulting from the difference in pressure between the top and bottom of an object immersed in water, exerts an upward force that counterbalances the weight of the object, allowing it to float or maintain a specific position in the water. The delicate balance between these two forces is crucial to stability and efficiency of movement in the water, especially in competitive swimming. The need for higher travel speeds will lead to an increase in propulsive forces (figure 1 and 2). During swimming, at constant speed, there must be a balance between propulsion force (Fp) and drag force (Fd): $Fp - Fd = 0$, suggested by Toussaint et al. (1992). Thus, the power required to overcome drag ($Pd = Fd \cdot v$) and the power required to push/pull the swimmer forward ($Pt = Fp \cdot v$) must be equal (Toussaint et al., 1992). To obtain the propulsive force, it was assumed that the average propulsive force would be equal to the average active drag values when the swimming speed was constant (figure 1) (Hollander et al., 1986).

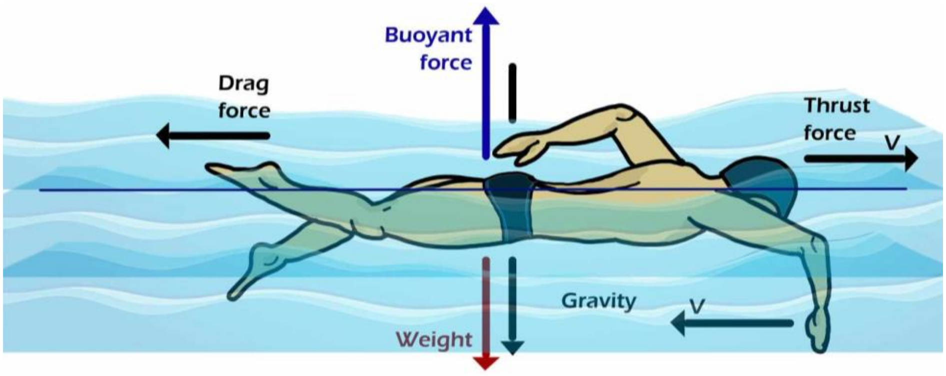

Figure 1. Schematic overview of the forces acting on the entire swimmer including the swimmer's upper and lower limbs. The driving force can be based on drag or lift, where active drag is carried out in the V direction (van Houwelingen et al., 2017).

The study of the force that promotes the swimmer's displacement and the force of the water that is exerted on the swimmer's body is essential to better understand the biomechanical needs that determine better sports performance (Alcock & Mason, 2007; Troup, 1999). When a swimmer moves through water, he/she generates propulsion through the action of the upper and lower limbs (as for example, referred to in figure 2) (Schleihauf, 1979). Unlike cyclical forms of locomotion (they can be various and even include running, cycling, among others), in swimming the application of force may or may not be constant during a cycle (Bartlett, 2014; Sanders et al., 2012). This application of forces can vary significantly throughout a stroke or kick cycle. This is due to the nature of the aquatic environment and the complexity of the movements involved in swimming (Schleihauf, 1979).

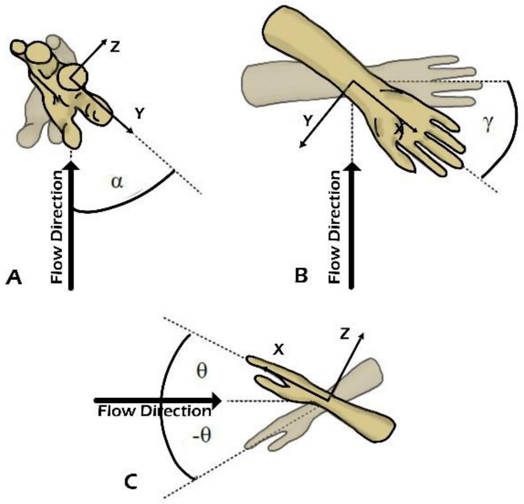

Figure 2. Definitions of different hand orientations in swimming as a means of propulsion. A: angle of attack Angle of attack, α (thumb lead: $\alpha = 0 - 90^0$, little finger lead: $\alpha = 90 - 180^0$), B: sweep angle γ (with $\theta = 0^0$), C: sweep angle slope θ (with γ = 90°). The positive x-axis is defined from the center of the wrist to the

tip of the long finger, the y-axis is defined from the little finger to the thumb side, and the z-axis is defined from the palmar side to the dorsal side of the hand (Sanders et al., 2012; and Schleihauf, 1979).

The application of Newton's Laws in the biomechanics of swimming plays a crucial role, especially in relation to the propulsion generated by the hands (Soh & Sanders, 2019). When a hand is moved through water, the water around the hand is displaced, creating a moving mass of water. According to Newton's third law, for every action, there is a reaction of equal magnitude, but in the opposite direction. Thus, when the hand pushes the water backwards, the water exerts a forward reaction force on the hand. This results in propulsion that moves the swimmer's body forward during the straight pull (Sanders et al., 2012; Soh & Sanders, 2019). Furthermore, when considering curvilinear traction, where the hand changes its direction during movement, a more complex interaction with the water is observed. Because the hand is curved, the surrounding water is accelerated in the opposite direction to the curve of the hand, generating a force that pushes the swimmer's body forward. This demonstrates how the change in the direction of traction can be used to generate additional propulsion in swimming (Schleihauf, 1979; Soh & Sanders, 2019).

To better understand the importance of propulsion, a study carried out by Bilinauskaite et al. (2013) sought to determine the hydrodynamic characteristics of scanned models of the swimmer's hand for various combinations of attack angle and sweep angle, shape and speed of the swimmer's hand, simulating separate underwater stroke phases of freestyle swimming (front crawl). Showing that the force and C_D varied at different flow velocities across all hand shapes and the variation was observed for different hand positions corresponding to different phases of the stroke (as also present in figure 2). The hand models with adducted and abducted thumb generated the highest drag and C_D forces. Suggesting that realistic variation of both the orientation angle influenced higher values of drag, lift and resultant coefficients and forces. To increase the net force, which affects the swimmer's propulsion, the swimmer must focus on effectively optimizing the reachable areas of the hands during crucial propulsive phases (Bilinauskaite et al., 2013; Sanders et al., 2012).

Therefore, there is great complexity in human aquatic locomotion (in this case swimming) and how it differs from terrestrial locomotion. While on dry land movement is driven by contact with the ground, in water the swimmer needs to create "immovable support" in the moving fluid medium (Williams, 2000). This is achieved through the interaction of body segments with water, taking advantage of its density and viscosity to generate propulsion and overcome resistive forces, such as hydrodynamic resistance. Hydrodynamic resistance manifests itself in two main ways: as a force that slows the swimmer's movement in the water and as a reaction force to the movements of the swimmer's limbs (manifested for example by figure 1 and figure 2). This hydrodynamic reaction force is essential to drive the swimmer's locomotion in the water. Swimming speed depends on the magnitude and direction of the hydrodynamic reaction, created by limb movements, and the active hydrodynamic resistance (Williams, 2000). During the swimming movement cycle, the value and direction of the hydrodynamic reaction and active hydrodynamic resistance constantly change due to changes in the working and recovery phases of limb movements. These dynamic changes in effective tractive force and active hydrodynamic resistance are fundamental to understanding the mechanics of swimming and optimizing the efficiency of the swimmer's movement in the water (Williams, 2000).

Hydrodynamic drag

Regarding resistive forces, these are difficult to quantify due to the controversy surrounding the ability to measure this force (Vilas-Boas et al., 2010). There are still few reviews that discuss resistive forces or drag forces. With advances in technologies and techniques, an updated review (study 1) is needed to ensure that swimming scientists and coaches can accurately and effectively incorporate endurance testing into athlete preparation and performance analysis (Rushall, 1994; Sanders et al., 2012; Sacilotto et al., 2014; Toussaint & Beek, 1992).

Therefore, it is important to remember that water resistance or drag (D, N) is defined as one of the main determinants of the energetic cost of swimming (E_c) at a specific speed, as shown by the following equation:

$$E_c = (W_d/\eta_P) \cdot \eta_O^{-1} \qquad (1)$$

where E_c represents the energy spent to cover a unit of distance at a given speed (generally expressed in J m/s), η_P and η_O are the propulsive efficiencies, and W_d (J m/s) is the work expended per unit of distance to overcome hydrodynamic resistance (i.e. D, N) (Zamparo, 2006). Therefore, when performing strokes, the objective is to optimize speed by increasing propulsion and reducing drag (Zamparo et al., 2020). Drag is the force that swimmers must overcome to maintain the translation of their center of mass (Kjendlie & Stallman, 2008). It can be expressed by Newton's equation as:

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

Where D is the drag force (in N), ρ is the water density (in kg/m3), v is the swimming speed (in m/s), S is the projected frontal surface area (FSA) of swimmers (in m2) and C_D is the drag coefficient (changing according to shape, orientation, and Reynolds number). As given by equation (1), it is also determined by:

$$D = W_d \cdot (J\frac{m}{s} = N) \qquad (3)$$

Determining drag during swimming (D_A, active drag) is therefore a fundamental issue in the assessment of swimming performance. However, while hydrodynamic drag determined by towing a non-swimming subject through water (passive drag, D_P) has been investigated for over a century, direct determination of D_A has been studied since 1986 by Hollander. Although several methods for estimating it have been described in the literature (for measuring D_A) (Wilson & Thorp, 2003). As mentioned previously, it has been reported that estimated D_A is two to three times greater than D_P (di Prampero et al. 1974), but also equal to or less than D_P (Kolmogorov & Duplisheva 1992; Toussaint et al. 1988). Standardizing the calculations of the component variables to produce the same resulting criterion may explain some of the variability in the measurement of drag force (Havriluk, 2005). Where equation (2) shows us that drag has a proportional relationship between the variables given as:

$$C_D = 2D/\rho \cdot S \cdot v^2 \cdot \ FSA \qquad (4)$$

where C_D is the drag coefficient, D is the drag force, ρ is the mass density of the water, S is the cross-sectional area of the body and v is the speed. The C_D considers differences due to body size and provides the most appropriate measurement criterion.

In the case of hydrodynamic drag, S mostly corresponds to the body projection area (FSA), in its transverse plane (as for example in figure 3).

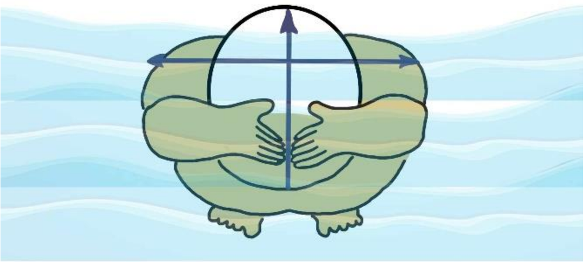

Figure 3. Schematic orientation of the swimmer's maximum sectional area in ventral glide, designated as FSA, identified in its transverse plane in relation to the direction of application of D, opposite to the direction of force application (adapted from Clarys, 1979).

In addition to FSA, swimming technique plays a crucial role in determining the drag force experienced by a swimmer. Excessive lateral movements of the body or uncontrolled foot tapping can compromise the hydrodynamics of the swimmer's body, resulting in an increase in hydrodynamic resistance (Zamparo et al., 2009; Pendergast et al., 2005). Zamparo et al. (2009) and Pendergast et al. (2005) indicate that effective training can help reduce hydrodynamic resistance, even in elite swimmers. This highlights the importance of emphasizing not only FSA but also technical precision during training. Therefore, swimmers and coaches should focus not only on reducing FSA, but also on improving swimming technique to minimize hydrodynamic resistance and, consequently, improve performance efficiency in the water. This highlights the need for a holistic approach to training, considering both physical and technical aspects to optimize swimmers' performance, in addition to the importance of not studying just one specific factor in swimming.

Therefore, it is important to consider the position of the swimmer's body in the water and its relationship with hydrodynamic resistance (Vorontsov & Rumyantsev, 2000). When a swimmer assumes a more horizontal position with the water surface, as shown in figure 4, he takes up less space and interrupts the flow of water molecules around him less. This results in a reduction in the drag force experienced by the swimmer (Costill et al., 1995; Vorontsov & Rumyantsev, 2000). Just like hand position, along with propulsion, this also plays a significant role in reducing hydrodynamic resistance and optimizing swimming efficiency. When the swimmer's hand enters the water, it is important that it is positioned in such a way as to minimize turbulence and interruption of the water flow around it, as can be seen in figure 5. Ideally, the hand should enter the water smoothly and with fingers slightly spaced, forming a wide, flat surface to push water back. This helps create efficient propulsion by harnessing water to generate thrust without unnecessarily increasing resistance (Cohen et al., 2015; Hollander et al., 1986; van Houwelingen et al., 2017). Furthermore, during the pulling phase (figure 4), the hand must be kept in a firm position, with the fingers extended and the palm facing backwards. This allows the hand to make the most of the available surface area to push water backwards, generating propulsion while reducing hydrodynamic resistance (Cohen et al., 2015; Hollander et al., 1986). Therefore, just like body position, hand position in the water is essential to minimize resistance and maximize swimming efficiency (van Houwelingen et al., 2017). Proper technique, combined with ideal hand position, can help swimmers improve their performance in the water and achieve faster times (van Houwelingen et al., 2017). On the other hand, when a swimmer adopts an oblique body position, with a downward slope from head to toe, as in the image below, he occupies more space in the water and generates greater hydrodynamic resistance (Costill et al., 1995). Furthermore, trying to keep the head and shoulders elevated in this position can lead to a deeper kick, further increasing the tilt of the body and, consequently, the drag force (*D*). Therefore, to minimize hydrodynamic resistance and improve swimming efficiency, it is recommended that swimmers remain as horizontal as possible while moving through the water. This highlights the importance of swimming technique and body position in the water as key elements to optimize performance in competitive swimming (Costill et al., 1995).

Figure 4. Resulting from the combination of drag, glide and propulsion, in the space occupied by the swimmer, causing hydrodynamic drag (adapted from Costill et al., 1995 and Vorontsov & Rumyantsev, 2000).

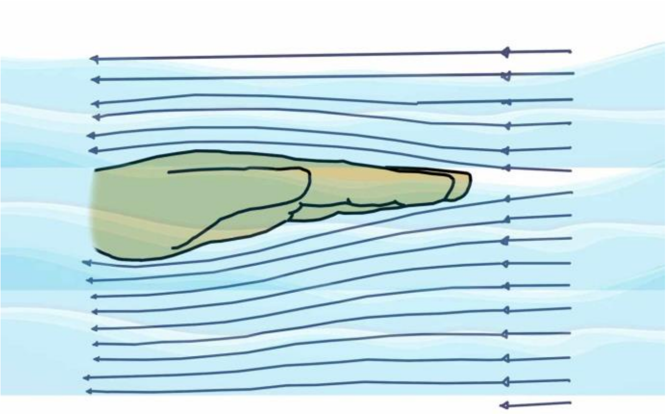

Figure 5. Resulting flow, drag and refraction in the direction of the projection of the swimmer's hand, causing hydrodynamic drag (adapted from Costill et al., 1995 and Marinho et al., 2010).

Taking this information, we reasoned that it would be important to carry out a review on D_A in swimming (including experimental and numerical studies) realizing that this is crucial, given the importance of this phenomenon for swimmers' performance (study 1) (Lopes et al., 2022). Since swimmers spend their races moving through the water, understanding how drag affects their performance is essential to optimizing swimming technique and maximizing speed (Lopes et al., 2022). Comprehensive review on D_A in swimming would have to include (1) Experimental studies investigating hydrodynamic drag in swimmers during different swimming styles (crawl, backstroke, breaststroke, butterfly) and in different conditions (speeds, depths, body positions); (2) Numerical studies that use computer simulations to model the water flow around the swimmer's body and calculate drag in different situations; These two phenomena include (3) analysis of swimming techniques and their influence on D_A, including body position, trunk rotation, hand entry into the water, traction phase of the stroke, among other factors described in the study 1; (4) Investigation of strategies to reduce D_A according to the authors/studies carried out, such as the use of low-drag swimsuits, improving swimming technique and specific training to improve the body's hydrodynamics (Lopes et al ., 2022). This way, it is possible to synthesize this information so that it can provide valuable insights for coaches, swimmers and researchers interested in improving performance in the water, as well as carrying out new studies, new projects and application methodologies. This could lead to significant advances in understanding the biomechanics of swimming and developing more effective training and competition strategies (Troup, 1999).

Total drag consists of three components: frictional drag (depends on the friction between the skin and the water); pressure drag (depends on body surface area); wave drag (depends on the deformation of the water surface) (Toussaint & Beek, 1992). Therefore, it is necessary to understand that there is an increased tendency for there to be errors or contradictory conclusions, it is enough for a variable or a logical proposition to be defined differently. It is necessary to describe with description which method should be used (with some caution) and assumes that pressure drag is responsible for most of the total hydrodynamic resistance. However, the contribution of pressure drag to D depends on the speed (the higher the speed, the lower its contribution); the reliability of these calculations, therefore, also depends on the speed used (Zamparo et al., 2009). The method used by Zamparo et al. (2009) demonstrates that it can be applied in a "safe" way to estimate drag up to speeds of 1.4 m/s (at which pressure drag is about 63% of D); this could not be the case at higher speeds where the pressure drag contribution is reduced.

According to equations 2 and 3, assuming a constant value of ρ (997 kg/m^{-3} at 25ºC), the D/v^2 relationship depends only on the values assigned to FSA. Thus, a horizontal relationship D/v^2versus v suggests that FSA remains unchanged at different speeds, a descending one indicates that FSA decreases with v, and an ascending one that FSA increases with speed (Lopes, et al., 2023; Morais et al., 2020; Zamparo et al., 2009).

The C_D is, by definition, proportional to D/v^2 (Vogel, 1994); therefore, changes in $D/v^2$with speed can be expected to reflect changes in C_D with v. On the other hand, the body tends to assume a more aerodynamic position in the water with increasing speed due to hydrostatic lift (Lavoie & Montpetit, 1986; Vorontsov & Rumyantsev, 2000), therefore it can be expected that D/v^2changes with the speed mirrors the FSA changes with v as well.

Despite the complexity of the aquatic environment (i.e., the properties of water), some progress has been made in understanding the kinetic domain. The forces in the water were estimated through direct and indirect methods, namely inverse dynamics, computational fluid dynamics (CFD), tethered or semi-tethered swimming systems and pressure sensors (all of them described and developed in the second topic of chapter 2 with the description: *Techniques used to measure drag in swimming through experimental and numerical methods*, on page 47).

Propulsion vs Drag, the necessary cohesion between the two forces and the influence on other variables in swimming

When analyzing these immense variables in swimming we realize that there is a significant gap in the literature about propulsion in swimming. Propulsion is a crucial element for athletes' performance, it has been measured and has been the subject of study in various scientific contexts. Pressure sensors and inertial measurement units (IMU's) have emerged as promising tools for capturing and analyzing swimmers' movements in the water (Hamidi Rad et al., 2021; Morais et al., 2022c). Some interesting studies that illustrate the use of these technologies were conducted, for example, by Fantozzi et al. (2016) and Santos et al (2022a). In these studies, researchers used IMU's to analyze upper limb kinematics and dynamics during different phases of the front crawl cycle (Santos et al., 2022b). By combining data from IMU's with information from pressure sensors placed on swimmers' hands, researchers were able to quantify not only the trajectory of the limbs, but also the propulsive force generated with each stroke. This provided a more comprehensive understanding of the propulsion mechanisms in crawl swimming (Fantozzi et al., 2022). A set of other relevant studies were carried out by Kadi et al. (2022) and Santos et al. (2023), where researchers investigated the relationship between swimming technique and swimmers' performance. Using pressure sensors and IMU’s placed on different parts of the body, the researchers were able to analyze in detail the distribution of force during each phase of the stroke, as well as the body's orientation and rotations during swimming. This analysis allowed us to identify specific movement patterns associated with better performance, providing valuable insights for coaches and athletes. Furthermore, advances in sensor technology have enabled more specific and detailed studies on the biomechanics of swimming. For example, recent research has explored the use of high-resolution pressure sensors to analyze the distribution of pressure across the surface of a swimmer's body during swimming, which can help identify areas of drag and improve swimming technique. These studies highlight the key role that pressure sensors and IMU’s have played in understanding swimming propulsion, providing valuable insights to optimize technique and improve athletes' performance (Hamidi Rad et al., 2021; Morais et al., 2022c; Santos et al., 2023). The continuous development of these technologies promises to open new perspectives for research and innovation in the field of aquatic biomechanics (Lopes et al., 2023). Three review studies on this topic (Magalhaes et al., 2015; Marinho et al., 2022; Morais et al., 2022c), which used IMU’s to investigate propulsion patterns in swimmers during different swimming styles. They found that the use of IMU’s provided a more detailed understanding of the movements and forces involved in propulsion, allowing useful insights to improve swimming technique and maximize efficiency in the water. In the study by Morouço et al. (2011) and Santos et al. (2016), in which researchers analyzed the relationship between swimming technique, propulsive force and swimmers' performance. Noticing that swimmers with a more efficient swimming technique tended to produce greater propulsive force and achieve better results in competitions. Despite these advances, there is still a significant need for more research into swimming propulsion, especially using technologies such as IMU’s for detailed movement analysis. Therefore, we sought through study 2 to help uncover more useful ways to improve elite swimming technique and provide valuable insights for training and improving the performance of swimmers (study 2) (Lopes et al., 2023).

Furthermore, C_D in competitive swimming plays a critical role in swimmers' performance, often being considered a more important aspect than drag or propulsion alone (as was later evidenced in study 3). Furthermore, studies of resistance forces largely use the absolute value of drag (D_A and D_P), however, it has been indicated that the C_D (C_{DA} and C_{DP}) better evaluate the swimmer's hydrodynamic profile (Barbosa et al., 2015a; Barbosa et al., 2015b; Vilas-Boas et al., 2010). When studying the hydrodynamic resistance faced by a swimmer (through a fluid, in this case water), it should be more common to use C_Ds to evaluate the hydrodynamic profile in a more precise way. Using C_D allows for a more direct comparison between different objects, regardless of size or shape, as it normalizes the drag force relative to the specific characteristics of the moving object (in this case the swimmer). This is particularly useful because minimizing resistance is crucial to improving performance. Therefore, when evaluating a swimmer's hydrodynamic profile, drag coefficients (C_D) such as C_{DA} and C_{DP} are more appropriate, as they provide a more accurate measure of the resistance faced during movement in the water. Several very recent studies such as Morais et al. (2023a) and Morais et al. (2024) are a clear example of this important tool, where they seek to find out whether C_{DA} and C_{DP} obtain more relevant or more pertinent values than D_A and D_P in absolute values. Morais et al. (2023a) analyzed the agreement of C_{DA} measured using drag (speed perturbation) and propulsion (Aquanex system) methods, using swimmers from a national swimming team. Determining that C_{DA} should be the main result used in interpreting the hydrodynamic profile of swimmers, as it is less sensitive to swimming speed (Morais et al., 2023a; Morais et al., 2023b). In a second study, the authors confirmed that C_{DP} is less dependent on swimming speed than D_P (Morais et al., 2024). D_P in this study was measured with a low voltage isokinetic motor at 1.2, 1.4, 1.6, and 1.8 m/s, but FSA was also acquired. In this way, it was possible to realize that C_{DP} should be the parameter of choice to monitor the hydrodynamic profile of swimmers, instead of the absolute value of D_P (Morais et al., 2024). Therefore, trainers and researchers should be aware that C_{DA} can also be calculated based on propulsion methods and not just based on drag methods, just as C_{DP} should be valued more than absolute values of D_A and D_P, although these are also important values to take into consideration. Therefore, the swimming community can now use various equipment to measure the hydrodynamics of their swimmers. We can say that this occurs because there is a (1) influence on speed: The C_D directly affects the swimmer's speed in the water. A high drag coefficient results in greater forward resistance and therefore a lower speed. Reducing the drag coefficient can help swimmers increase their speed without needing to significantly increase propulsive force; (2) Energy Efficiency, a lower C_D means that swimmers can reach a given speed with less effort, which results in greater energy efficiency. This is particularly important in long-distance races, where energy conservation throughout the race can be decisive for performance; (3) Swimming Technique, reducing the drag coefficient is often associated with a more efficient and hydrodynamic swimming technique. This involves proper body position, smooth entry into the water, an efficient stroke trajectory and good coordination between arms and legs. Improving swimming technique to reduce drag can lead to significant performance gains; (4) Competitiveness. In events where times are very close between competitors, such as in Olympic finals, small differences in the drag coefficient can make the difference between winning or losing a medal. Therefore, swimmers and their support teams dedicate significant time and resources to minimize drag and maximize efficiency in the water. Thus, C_D (through C_{DA} and C_{DP}, no less important) is a crucial aspect of competitive swimming, often considered more important than drag or propulsion alone.

The resistive forces that influence the swimmer in the water include shape, wave and frictional drag which are influenced by the swimmer's speed, boundary layer, shape, size and frontal surface area (FSA), as also noted in equation 2 (Morais et al., 2020). In swimming, the resistive forces are called drag D_A and D_P. D_A is the water resistance associated with the dynamic movement of swimming and D_P is the water resistance that a body experiences in a fixed or unchanging posture, such as a fixed hydrodynamic position (Chatard et al, 1990). Kolmogorov et al. (1997) confirmed that D_A varies between individuals and appears to be related to swimming technique and anthropometry. As noted in equation 1, in the context of swimming, the drag force represents the swimming drag, which can be a D_A or D_P.

Thus, several studies (Barbosa et al., 2015a; Morouco et al., 2014) indicate that displacement in swimming is based on a single force with two different types of manifestation (propulsive force and drag force). Vilas-Boas et al. (2001) sought to characterize the maximum hydrodynamic drag and maximum mechanical power in the front crawl technique in young Portuguese swimmers of both sexes and with high sporting potential. Concluding that: (i) the values of hydrodynamic drag when done at maximum speed are lower in younger swimmers and in top international male swimmers; (ii) hydrodynamic drag values at maximum swimming speed are higher in male swimmers than in female swimmers; (iii) C_D values tend to be higher in pre-junior swimmers compared to swimmers of the same age group and do not vary significantly with age and sporting level.

However, it is beginning to become clear that in-water assessments should mimic, as much as possible, the movement pattern of the body's limbs, leading to a more ecological environment (Barbosa et al., 2020). Although some previous systematic reviews have been carried out on indirect methods (Andersen & Sanders, 2018; Gomes & Loss, 2015; Takagi et al., 2015), the available literature on direct methods has not yet been gathered. This may help to gain a deeper understanding of methods that allow for the collection of drag data in conditions more like free swimming, i.e. for D_A (study 1). Furthermore, linking values of all types of force involved in this modality (propulsive and drag) with different methods, applicable in practice, becomes extremely useful for swimmers and coaches (study 2 and study 3). Knowing fully that it is extremely useful that data can be comparable between the same sample and not in different practice contexts (Mooney et al., 2016). Furthermore, the costs of different tools and protocols can hinder training monitoring.

Defining objectives for the study

The literature reports substantial information on swimmers' drag, indicating that swimmers who have a better hydrodynamic profile are more likely to perform better (Morais et al., 2021b; Narita et al., 2017). Therefore, it is important to consider that movement analysis in sports is considered the recording of sports movements and the subsequent calculation of significant parameters that describe the movement from raw kinematic data (Ferdinands, 2010). Therefore, the information provided to athletes is considered of great importance for improving their performance.

Completely different results are found when comparing different variabilities and drag forces. Namely, it is reported that the force of D_P and D_A present different values and that in turn D_P will be lower than the values of D_A, just as a body on the surface presents lower values while a greater drag force is found below the surface (Clarys et al., 1974; Jiskoot & Clarys, 1975). Another study (Lyttle et al., 1998) found a greater drag force on the surface. What is certain is that regardless of the results or type of study, they all have one thing in common, when comparing the data, there is clearly a positive or negative relationship between the swimming variables. That is, it seems that in different ways the different resistive forces of swimming are associated with performance, we just don't know with what direct or effective interaction.

More concretely, substantial differences were also found in the relationship between D_A and D_P. And there seems to be some discord mainly over time, probably due to evolution in the methodology applied or in the tools to obtain data and results. We can see that previous studies reported values for D_A that were twice those for D_P (Clarys, 1978; di Prampero et al., 1974), while more recent studies reported approximately equivalent values for D_A and D_P (Kolmogorov & Duplishcheva, 1992; Shimonagata et al., 1999). Other authors suggest that this discrepancy may simply result from different variables being used in the measurement or measurement error occurring (Hollander et al., 1986). In both cases, measurement variability of a magnitude that leads to completely different conclusions deserves further study or an attempt to understand whether there is a direct association for this effect (study 2 and study 3).

The study of the relationship D/v^2 versus v together with an analysis of how FSA changes with increasing speed, may therefore make it possible to investigate the interaction between C_D and FSA in determining hydrodynamic resistance in the range of speeds normally reached during swimming. If C_D turned out to be relatively constant over the range of speeds investigated, changes in D/v^2would be mainly due to changes in FSA and therefore the Da/v^2 ratio (during actual swimming) could be estimated: based on the Dp/v^2 ratio (evaluated during passive towing); and the difference in the effective frontal area between the two conditions (FSA_{active}: frontal area projected during swimming; $FSA_{passive}$: frontal area projected during passive towing). In this case, the D_A or C_{DA} could finally be calculated, at any speed, by multiplying the Da/v^2ratio by the square of the speed of interest.

In this sense, there was an opportunity to explore the different variables and associate them in a unique way to be able to share their importance in swimming performance, by carrying out a more in-depth analysis of the forces in the water in a more concrete way. So, first, it would be important to review D_A (experimental and numerical studies), since swimmers spend most of the race's swimming, in a higher percentage than D_P (from the start until the end of the race), representative of the first study. A secondary objective was to use a method that collects propulsive data and that is simple to understand and possible to use in the training methodology applied to coaches. This representative of the second study, highlighting that there is currently still little information and few studies on propulsion itself, during the recurring year of testing, mainly with pressure sensors and IMU's. Regardless of the equipment used, data processing (after data collection) may not be user-friendly for coaches and swimmers. In other words, data often needs to be filtered and manipulated to be presented to coaches and swimmers. In this way, the second study sought understand the variation of a set of kinematic and kinetic variables between two swimming sections and their relationship with swimming speed (where C_{DA} was included), as well as understand the advantages of using wearables to measure propulsion in swimming. As well, we still try to monitor the forces in the water more regularly and obtain concrete data for decision making, whether for the purposes of improved technique or long-term progress and evaluation. Finally, in the third study we sought to demonstrate in a more emphatic way the importance of C_D as a fundamental role in competitive swimming and in general, as there is a direct influence on the swimmer's speed in the water. Never forgetting that the greater the drag, the more difficult it is for the swimmer to maintain a high speed. Thus, C_D is determined by several factors, including the swimmer's body shape, swimming technique, body position in the water (through FSA) and the turbulence created by the movement. Swimmers with a more hydrodynamic body position and more efficient swimming technique generally have a lower C_D, meaning they face less resistance and can swim faster for a given amount of effort. The third study showed that C_D is one of the most important factors to consider, more than drag or propulsion values alone. Simply because swimmers are constantly looking for ways to reduce their C_D to maximize their speed in the water. The objective of this thesis was to outline the methodologies used to study strength, and to search within them for those that are most suitable in a practical way during everyday life. At the same time, we sought to understand whether the use of wearables to monitor swimmers' propulsive force to obtain real-time feedback and understand its relationship with swimming speed would be viable. Then investigate the comparison of C_D's (C_{DA} and C_{DP}) in a unique way, relating it to the FSA.

This thesis was developed according to the following sequence:

- Chapter 2 presents a systematic review based on the available literature on the methods used to assess swimming drag:
    - Study 1 describes which numerical and experimental methods are used to evaluate D_A in human swimming;
    - A no less important subchapter is added, with the techniques used to measure swimming drag through experimental and numerical methods. This chapter sought to be practical and discriminatory for swimmers and coaches in a simpler and more detailed way.
- Chapter 3 shows the experimental studies developed to achieve the main objective of this thesis:
    - Study 2 sought to understand the variation of a set of kinematic and kinetic variables between two swimming sections and their relationship with swimming speed;
    - Study 3 compared C_{DP} with C_{DA} at the same speed. Checking whether C_{DA} would be significantly greater than C_{DP} at the same speed, and whether this difference would be similar to that found between propulsion and drag.

Then, there is a general discussion of the results of the studies carried out (Chapter 4), followed by the main conclusions and limitations of the thesis (Chapter 5). Some suggestions for future research are also presented (Chapter 6). To better convey the procedures to the public, as well as limitations and constraints, some complementary presentations were made previously and are presented in Appendix I-II.

Chapter 2. Literature review and description of methods

Study 1. Numerical and experimental methods used to evaluate active drag in swimming: A systematic narrative review

Abstract

Introduction: In swimming, it is necessary to understand and identify the main factors that are important to reduce active drag and, consequently, improve the performance of swimmers. However, there is no up-to-date review in the literature clarifying this topic. Thus, a systematic narrative review was performed to update the body of knowledge on active drag in swimming through numerical and experimental methods.

Methods: To determine and identify the most relevant studies for this review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was used.

Results: 75 studies related to active drag in swimming and the methodologies applied to study them were analyzed and kept for synthesis. The included studies showed a high-quality score by the Delphi scale (mean score was 5.85 ± 0.38). Active drag was included in 7 studies through numerical methods and 68 through experimental methods. In both methods used by the authors to determine the drag, it can be concluded that the frontal surface area plays a fundamental role. Additionally, the technique seems to be a determining factor in reducing the drag force and increasing the propulsive force. Drag tends to increase with speed and frontal surface area, being greater in adults than in children due to body density factors and high levels of speed. However, the coefficient of drag decreases as the technical efficiency of swimming increases (i.e., the best swimmers (the fastest or most efficient) are those with the best drag and swimming hydrodynamics efficiency).

Conclusion: Active drag was studied through numerical and experimental methods. There are significantly fewer numerical studies than experimental ones. This is because active drag, as a dynamical phenomenon, is too complex to be studied numerically. Drag is greater in adults than in children and greater in men than in women across all age groups. The study of drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming. Although most agree with these findings, there is disagreement in some studies, especially when it is difficult to define competitive level and age. The disagreement concerns three main aspects: (1) period of the studies and improvement of methodologies; (2) discrimination of methodologies between factors observed in numerical vs experimental methods; (3) evidence that drag tends to be non-linear and depends on personal, technical, and stylistic factors. Based on the complexity of active drag, the study of this phenomenon must continue to improve swimming performance.

Keywords: active drag, water resistance, biomechanics, assisted swimming, resisted swimming

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Introduction

Swimming performance concerning humans is poor compared to species whose habitat is aquatic. In fact, the maximum swimming speed performed by humans represents about 16% of the maximum speed obtained by aquatic species (Toussaint, Roos, & Kolmogorov, 2004). One of the reasons for this difference in speed is the greater resistance humans encounter when moving through the water (Toussaint, Roos, & Kolmogorov, 2004).

A swimmer's displacement relies on the net balance between propulsion and drag (Zamparo, Cortesi, & Gatta, 2020):

$$a = \frac{T-D}{m} \qquad (1)$$

In which a is the acceleration (in m/s^2), T is the total propulsive force, i.e., thrust (in N), D is the total drag force (in N), and m is the total mass (i.e., swimmer's body mass plus the added mass of water, in kg). This is critical to understanding the biomechanical needs that determine better swimming performance. Therefore, when performing swimming strokes, the goal is to optimize speed by increasing propulsion and reducing drag (Zamparo et al., 2020). Drag is the force that swimmers must overcome to maintain the translation of their center of mass (Kjendlie & Stallman, 2008). It can be expressed by Newton's equation as:

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

In which D is the drag force (in N), ρ is the density of water (in kg/m^3), v is the swimming speed (in m/s), S is the projected frontal surface area (FSA) of the swimmers (in m^2) and C_D is the coefficient of drag (changing according to shape, orientation, and Reynolds number).

The total drag consists of three components: (1) friction drag (depends on the friction between the skin and the water); (2) pressure drag (depends on body surface area); (3) wave drag (depends on the water surface deformation) (Toussaint & Beek, 1992). Based on these components, total drag can be computed as:

$$F = F_f + F_p + F_w \qquad (3)$$

In which F (in N) is the total drag force, F_f is the friction component (in N), F_p is the pressure component (in N), and F_w is the wave component (in N). Overall, it is generally accepted that frictional drag is the component with the smallest contribution to total drag, especially at higher swimming velocities (Bixler et al., 2007). Nonetheless, friction drag should not be disregarded in elite level swimmers. On the other hand, pressure drag and wave drag represent the most important part of the total drag, especially when performing a swimming stroke (Toussaint and Beek, 1992). Therefore, swimmers must intensify the most hydrodynamic postures during swimming.

Indeed, the literature reports two types of drag: (1) passive drag; (2) active drag. Passive drag (D_P) is the evaluation of the drag produced during the displacement of a towed body (i.e., without relative movement of the body segments in the aquatic environment) (Pendergast et al., 2006). Active drag (D_A) is the water resistance induced to a body while swimming (Kolmogorov & Duplishcheva, 1992). Studies on D_A are more common because during a race swimmers spend most of their time performing strokes (Morais et al., 2019).

In 1974, di Prampero et al., developed and used a method to evaluate drag during real swimming conditions through an energetic approach. All recent overviews of a swimmer's drag have confirmed this statement (González-Ravé et al., 2022; Keys & Lyttle, 2007, Morais et al., 2019, Sacillotto et al., 2014, Zamparo et al., 2020). Both types of drag and its components can be measured by numerical and experimental methods. The former (i.e., numerical methods) is a virtual prototype of the product of interest represented by a system of equations based on a mathematical theory, such as computational fluid dynamics (CFD) (Takagi et al., 2016). The latter (i.e., experimental methods) is a method in which the variables are manipulated in a pre-established way and their effects are sufficiently controlled and known by the researcher for the observation of the study (Takagi et al., 2016). CFD is one of several methods that have been applied in sports research to observe and understand the water flow activity around the human body and its application to improve swimming technique, equipment, and performance (Marinho et al., 2011; Keys & Lyttle, 2007). Smooth particle hydrodynamics (SPH) is a numerical method without a Lagrangian mesh, which allows a detailed quantitative analysis of swimming stroke variations and kinanthropometric variations. It is important to mention that there are few studies that use numerical methods to study D_A. Bixler and Schloder (1996) introduced two-dimensional CFD applied to swimming science. More recently, Cohen et al. have made progress in this method as they are the authors of some studies on numerical methodology that provide some interesting data (Cohen et al., 2015; Cohen et al., 2018; Cohen et al., 2020). However, in one of their studies, they mention that the angles of attack of the hands were compared with the contribution of lifting and dragging the hands to generate thrust in the direction of the current. This study allowed the investigation of possible connections between performance and asymmetries during swimming. Efficiency is negatively affected because periods of very high velocity consume exaggerated amounts of energy, considering that drag is non-linearly dependent on instantaneous velocity. Thus, a greater coefficient of variation of the swimmer's speed suggests a lower swimming efficiency (Cohen et al., 2018; Cohen et al., 2020).

Based on experimental methods, D_A can be measured through three approaches: (1) measurement of active drag (MAD) (Hollander et al., 1986); (2) velocity perturbation method (VPM) (Kolmogorov & Duplishcheva, 1992); (3) assisted towing method (ATM) (Alcock & Mason 2007), and; (4) measurement of residual thrust (MRT) (Narita, Nakashima & Takagi, 2017). To determine D_A through experimental studies, it was found that MAD, VPM, and ATM are now commonly used to obtain D_A values accurately to assess swimmer technique (Formosa et al., 2012; Hazrati et al., 2016; Toussaint et al., 2004). The MAD system consists of pushing pads while the swimmer moves in the water performing the natural swimming movement (as much as possible) (Hollander et al., 1986). The thrust pads fixed below the water allow for the generation of propulsion without loss of energy (Formosa et al., 2012). The ATM system is relatively new compared to the MAD and VPM systems (Hazrati et al., 2016). The ATM system was developed identically to the bases of the VPM, except that it uses assisted towing and resisted swimming (Toussaint et al., 2004), as similar conditions are required in both tests. The main difference between the two is that the ATM produces D_A profiles and intra-course propulsion, rather than just an average measure of D_A (Formosa et al., 2012). The MRT method, which was recently developed, allows the estimation of drag in swimming using measured values of residual thrust (Gonjo et al., 2020; Narita et al., 2017; Narita et al., 2018b). Through this method, it is possible to investigate D_A at various speeds without neglecting the influence of stroke length.

As stated by Toussaint et al., 2004, it is known that human performance in water is dependent on many variables in addition to innate ones. In this way, we must consider all the variables that can compromise a better performance. Thus, these variables depend not only on their propulsive abilities but also on their ability to reduce to a minimum the drag forces that involve the body in a hydrodynamic way (Taïar et al., 1999). Studying active drag becomes relevant simply because it corresponds to the very act of swimming in a cyclical way, which consists almost of the entire race in high competition (Kolmogorov & Duplishcheva, 1992). Considering the importance that the measurement of drag has on swimming performance, it can be said that the evidence in the literature has not been systematically or narratively summarized, specially including studies based on both numerical and experimental measurements. It must be mentioned that Sacilotto, Ball and Mason (2014) underwent a literature review on drag that also included numerical studies. The authors performed a biomechanical review of the techniques used to estimate or measure resistive forces in swimming. Therefore, the aim of this study was to carry out a systematic narrative review focusing on D_A (and its components) measured by numerical and experimental methods.

Methods

Literature search and article selection

Studies that analyzed D_A in swimming were searched in the following databases: Web of Science, Scopus, PubMed, and Science Direct. These electronic search databases were chosen as the most common databases related to methodological approaches in biomechanics applied to sport (framework, methodology, performance, and engineering). The studies that were selected met the following pre-defined inclusion criteria: (1) follow the criteria defined in Table 1; (2) are observational or intervention studies, (3) are written in English, (4) are published in a peer-reviewed journal; (5) involve fully healthy real human swimmers (or their three dimensional scans – 3D); (6) include tests performed to determine D_A in swimming; (7) are related to the analysis of human movement in the aquatic environment; (8) use numerical and experimental methods.

Review articles, conference articles and books, studies including animals, and publications not related to the topic in question were excluded from the analysis. Studies with disabled swimmers were also excluded from this review. The Preferred Reporting Items for Systematic Reviews flow diagram (PRISMA in Figure 1) characterizes the identification, screening, verification of eligibility, and inclusion of the studies. PRISMA describes the flow of information through the different phases of a systematic review and includes maps or number of identified, included, and excluded records and reasons for exclusion.

The Patient/Problem, Intervention, Comparison and Outcome (PICO) search strategy is shown in Table 1. It presents the words used to carry out the research, supported by the words most used by the authors to describe their studies. Each title, abstract, and keyword field of the text was identified and carefully read for the first selection of journal articles. If any of these fields (title, abstract, and keywords) was not clear on the topic under analysis, it was necessary to read and review the entire article in question to ensure its inclusion. For the initial research, a Boolean search strategy was used based on a combination of keywords that can be seen in Table 1. After excluding all unrelated and duplicate articles, 75 articles were selected for the final published review (Figure 1), comprising studies from 1986 until the end of the review research on January 31st, 2022, as this was the latest study framed within the pre-defined selection model. From the selected articles, the reviewers extracted information about the aim of the study, the participants, the methods to measure the D_A in swimming, the characteristics of the numerical and experimental method (s), the measured variables, and the data analysis used.

Table 1. PI(E)CO (P – patient, problem or population; I – intervention; E – exposure; C – comparison, control, or comparator; O – outcomes) search strategy.

Population	Intervention or Exposure	Comparison (design)	Outcome
Swimmer*	Development	Cross-sectional	Passive drag
Athlete*	Long-term development	Longitudinal	Active drag
Boy*	Biomechanics	Experimental	Drag
Girl*	Strength and conditioning	Descriptive	Performance
Young*	Performance	Randomized control trial	Coefficient of drag
Paralympic*	Competitive	Numerical	Mechanical power
Men*		CFD	Assisted swimming
Women*		MAD-System	Resisted swimming
Male*		VPM	Forces
Female*		Computational fluid dynamics	Drag forces
		Quantitative analysis	Biomechanic
		ATM	Power input
			Power output
			Mechanical
			Water resistance
			Coefficient
			Friction
			Inverse dynamics
			Posture
			Hydrodynamic
			Resistance
			Balanced position
			Alternative fluid dynamic
			Underwater
			Body position
			Breaststroke
			Backstroke
			Front crawl
			Freestyle
			Butterfly
			Balance

* – truncation to retrieve words with different endings.

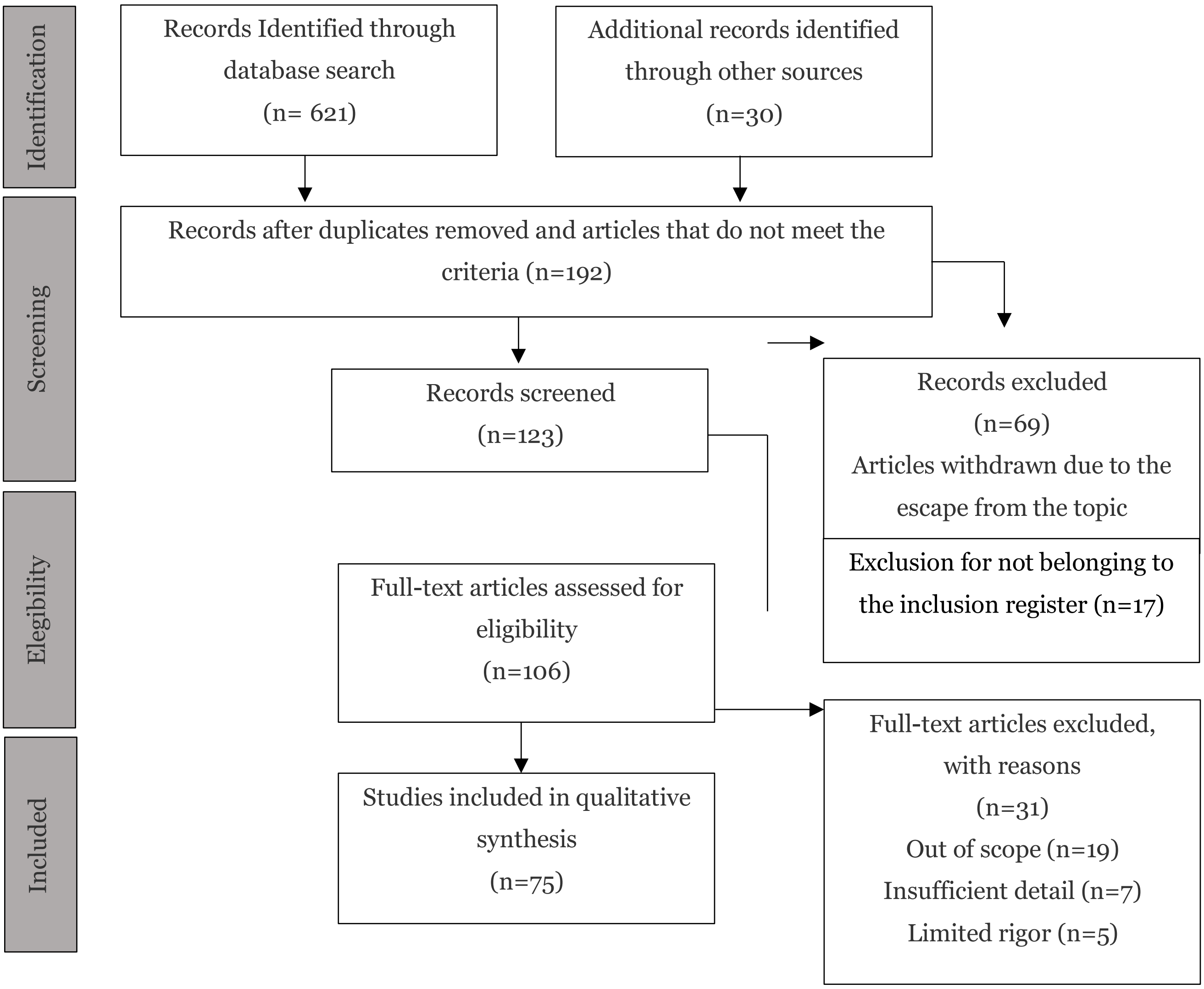

Figure 1. Flow diagram (PRISMA) representing the article selection process and the different phases of paper selection for the systematic review.

Quality assessment

The Delphi method was used to assess the quality of the selected articles (knowing that Delphi is a process to develop a scale suitable for the purpose). It was noted that this approach (i.e., applying and creating a group scale) is an indicator of methodological quality (de Meyrick, 2003; de Morton, 2009). The Delphi method aims to structure a process of collective communication allowing a group of researchers to deal with a complex problem (de Meyrick, 2003). This method allows the creation of an evaluation scale for the articles selected for this study (de Meyrick, 2003; de Morton, 2009). Particularly when accessing numerical studies, there is a need to create a specific questionnaire and scale. Thus, it was agreed among the authors to create a questionnaire that would make the decision on the classification of the studies selected for this narrative review unanimous. In this way, through the Delphi method, the authors attempted to evaluate the following questions: (1) Does the contemplated content meet the objective?; (2) Was there a logic in the used methods?; (3) Were the methods and subjects well defined?; (4) Was there writing, language and clarity in the presentation of the contents covered?; (5) Was the presentation of the results clear?; (6) Are the results consistent with the culture of the study? Two independent reviewers read all articles and scored according to the items on the scale (poor quality if scored ≤ 2; fair quality if scored 3 to 4; high quality if scored 5 to 6) (de Meyrick, 2003; de Morton, 2009). Subsequently, Cohen's Kappa (K) was calculated to assess agreement between reviewers. It was interpreted as (1) no agreement if $K \leq 0$; (2) none to slight if $0.01 < K \leq 0.20$; (3) fair if $0.21 < K \leq 0.40$; (4) moderate if $0.41 < K \leq 0.60$; (5) substantial if $0.61 < K \leq 0.80$; (6) almost perfect if $0.81 < K \leq 1.00$ (McHugh, 2012). After reviewing all articles, the Delphi scale showed a mean score of 5.85 ± 0.38 (i.e., high quality if scored), and Cohen's Kappa an almost perfect agreement between reviewers ($K = 0.651$, $p < 0.001$). The Delphi scores are presented in tables 2 and 3 for each article.

Results

A total of 75 studies met the inclusion criteria, of which 7 used the numerical method and 68 the experimental method. The criterion for defining which studies to include was unanimous, and so it was decided to consider all studies regardless of their type of method. However, it was essential that the topic of the study followed the needs described in table 1.

Tables 2 and 3 present a summary of the included studies, indicating the authors, year of publication, objective, number of participants, if applicable, and main results, for studies based on numerical and experimental methods, respectively.

Seven studies analyzed D_A based on numerical methods (including 5 studies on front crawl, 2 on backstroke, 4 on butterfly, and 1 on breaststroke (considering front crawl and dolphin kick), in which some studies include several techniques) (Table 2). All studies used swimmers as a sample, despite being models (scans of athletes or three-dimensional programming of at least one or more swimmers as their sample). Sixty-eight studies analyzed D_A based on experimental methods (including 64 studies on front crawl, 6 on backstroke, 2 on butterfly, and 6 studies on breaststroke (considering front crawl and dolphin kick)) (Table 3). They used human swimmers in their entire sample, all with effective experience in the modality and training.

Table 2. Summary of the objective, sample demographics, and main results of the studies related with D_A for numerical methods.

Study (year)	Objective	Subjects (age and competitive level)	Results	Delphi score Mean ±1SD
Cohen et al., (2012)	Determine the relative importance of the extension kick (often called downbeat) compared to the flexion kick (often called upbeat) in dolphin kick swimming	Smoothed Particle Hydrodynamics (SPH). Laser scans of athletes are used to provide realistic swimmer geometries in a single anatomical pose. These are rigged and animated to closely match side-on video footage	Swimmer strength depends on kick frequency and is insensitive to ankle flexibility. The maximal drag force occurs in the direction of the current, corresponding to the periods before the inversions of strokes, and swimmers must pay attention to the rapid inversions of direction	5.0±0.0
Cohen et al., (2014)	Determine the pitching effects of buoyancy during all competitive swimming strokes (front crawl, backstroke, butterfly, and breaststroke)	Laser body scans of national-level athletes and synchronized multiangle swimming footage were used in a novel markerless motion capture process to produce three-dimensional biomechanical models of the swimming athletes	Variation in buoyancy torque is much larger during breaststroke and butterfly than during front crawl and backstroke; pitching swimmer moment of inertia varies much more for butterfly and breaststroke than for front crawl and backstroke; that buoyancy torque and pitching swimmer moment of inertia are anticorrelated during butterfly and breaststroke	5.0±00
Cohen et al., (2015)	A combination of kinematic data and SPH-based flow modeling was used to explore the degree to which the instantaneous impulse generated by the arms is controlled by the trajectories of the hands, their orientation and speeds during the front crawl stroke.	SPH fluid model is used to analyze the thrust and drag generation of a front crawl swimmer. The swimmer model was generated using a three-dimensional laser body scan of the athlete and digitization of multi-angle video footage (CFD)	Two large distinct peaks in liquid thrust coincide with underwater strokes. The movement of the hands generates vortex structures that travel along the body (there is the production of lift and drag)	6.0±0.0
Cohen et al., (2018)	Investigate how the streamwise speed and net streamwise forces of the swimmer vary throughout the phases of the stroke. The dependence of the relative thrust from the arms compared to the legs on the stroke rate was also investigated	A dynamic biomechanical model of a female national-level swimmer was generated from a three-dimensional laser body scan of the athlete and multi-angle videos of sub-maximal swimming trials (CFD)	The Froude number varies from 0.40 to 0.31, meaning that the swimmer swims close to Fr=0.42 (hull speed), consequently the drag of waves on the surface is significant	6.0±0.0
Cohen et al., (2020)	The asymmetrical front crawl swimming performance of a male elite level swimmer who breathed every second arm stroke (unilaterally) was investigated	A laser body scan and multi-angle video footage of the athlete were used to generate a swimming biomechanical model (one male elite level)	The natural asymmetrical performance with the swimming movement acquired through the frontal area results in a greater D_A (swimmer's technique) are the main findings. These will help improve athletes' performance and coaches' decision making	6.0±0.0
Keys & Lyttle, (2007)	Sought to discriminate between the D_A and propulsive forces generated in underwater dolphin and flutter kicking using the CFD technology	A 3D image of an elite swimmer was animated using results from a kinematic analysis of the swimmer performing two different patterns of underwater dolphin kick (large/slow kicks versus small/fast kicks) and the underwater flutter kick	Advantage in using the swim kick in the underwater flutter kick over the small/fast or large/slow kick at 2.18 m/s There are benefits in prescribing techniques through the use of CFD models	6.0±0.0
Yuan et al., (2019)	Find the mechanism of the hydrodynamic interaction between human swimmers and to quantify this interactive effect by using a steady potential flow solver	Only interested in the wave drag component. No attempt is made here to analyze the other drag components due to the viscosity of the fluid. One passive swimmer; three swimmers in competitive swimming; and another observations	Showed that the hydrodynamic interaction made a significant contribution to the drafter's wave drag. By following a leading swimmer, a drafter at wave-riding positions could save up to 63% of their wave drag at speed of 2.0 m/s and lateral separation of 2.0 m/s. When a drafter is following two side-by-side leaders, the drag reduction could even be doubled	5.0±00

D_A – active drag; CFD – computational fluid dynamics; SPH – coupled biomechanical-smoothed particle hydrodynamics; F_r – froude number; C_D – coefficient of drag; SD – one standard deviation.

Table 3. Summary of the objective, sample demographics, and main results of the studies related with D_A for experimental methods.

Study (year)	Objective	Subjects (age and competitive level)	Results	Delphi score Mean±1 SD
Barbosa et al., (2010b)	Develop a structural equation modeling (ie, path analysis) for D_A force based on selected anthropometric, hydrodynamic, and biomechanical variables in competitive young swimmers	16 male swimmers (12.50±0.51 years) with several competitive levels	Studying the D_A, it is advisable to increase the fit of the model and develop new equations specific for young swimmers, instead of using the models with adult/elite swimmers. 95% of the D_A was explained by the variables used in the model	6.0±0.0
Barbosa et al., (2013)	Compare speed fluctuation and drag force in young swimmers	12 boys (14.42±1.24 years) 11 girls (12.73±0.79 years) Voluntary swimmers at regional and national level	For D_A a the boys showed significantly higher values in the fluctuation ($\Delta=35.77$; $Z=-2.400$; $p=0.02$; $d=1.34$). There are no differences between the sexes for C_{DA} ($\Delta=1.49$; $Z=-0.739$; $p=0.49$; $d=0.04$). When controlling for velocity effects, there are moderate-strong and positive associations between velocity fluctuation and D_A (the greater the velocity fluctuation, the greater the drag forces)	6.0±0.0
Barbosa et al., (2014)	Classify swimmers based on kinematics, hydrodynamics, and anthropometrics	77 young swimmers (34 girls and 33 boys, 12.83±1.26 years and 1–2 Tanner stages) with at least 4 years of experience in competitive swimming	FSA was measured with photogrammetric technique on land and in hydrodynamic position (C_D). Kinematics, hydrodynamics and anthropometrics are determinant domains in which to classify and characterize young swimmers' profiles). C_{DA} was associated with high hydrodynamic profile ($F=21.025$; $p<0.001$)	6.0±0.0
Barbosa et al., (2015a)	Compare swimming power output between boys and girls and to model the relationship between swimming power output and sprinting performance in young swimmers	100 young swimmers (49 boys and 51 girls aged 12.51±0.77 years and 12.24±0.71 years, respectively; all in Tanner stages 1–2 by self-report). The sample included national record holders, national champions, and other talent swimmers	There was a significant and strong relationship between sprinting performance and power, as well as D_A ($0.02\leq p \leq 0.04$; $0.37\leq \eta^2 \leq 0.48$). Boys have greater power and thus perform better than girls. There were no sex differences for C_{DA}	6.0±0.0
Barbosa et al., (2015b)	Analyze the changes in the hydrodynamic profile of young swimmers over a competitive season and to compare the variations according to a well-designed training periodization	25 talented swimmers (13 boys: 12.64±0.81 years and 68.02±5.49 s personal best in short-course swimming pool at front crawl; 12 girls: 12.43±0.78 years old and 71.23±5.45 s personal best; both sexes in Tanner stages 1–2 by self-report at the beginning of the research)	No variable presented a significant sex effect. Swimming efficiency improved between moment 1 and 2. There was a trend for both D_A increase from moment 1 and 2, but being lower at moment 3 than at moment 1 (−4.37±39.36%). Over the course of a season, hydrodynamic changes occur in a non-linear fashion	6.0±0.0
Barbosa et al., (2019)	Compare the anthropometrics, biomechanics and energetics in young swimmers of different competitive levels	75 boys (between 11 and 13 years) with a broad range of performances were ranked based on their personal best time in the men's 100m front crawl event and then split-up into three tiers (Tier-1, i.e., top-tier, best performers; Tier-2, mid-tier; Tier-3, lower-tier)	Level 1 swimmers have higher drag than their peers due to their faster swimming. As a result, C_D is smaller, and there were significant variations for most of the selected variables (particularly for D_A), with a moderate-large effect size (D_A = (T1vT2 = $p<0{,}001$ (1.13 N); T1vT3 = $p<0{,}001$ (0.99 N))	6.0±0.0
Benjanuvatra et al., (2002)	Cross-sectional comparison between D_A and D_P buoyancy	9 (5 boys and 4 girls) national level swimmers	Comparing the Fastskin TM suits and the normal bathing suits, there were lower D_A force values (10.2%). There was also a significant difference for surface towing in the three speeds of 1.6, 2.2 and 2.8 m/s	6.0±0.0
Chatard & Wilson (2003)	Investigate the effect of the distance separating the lead and draft swimmers on the metabolic and hydrodynamic responses of the draft swimmer	Part I - 11 males (24±5 years) Part II - 6 males (23±4 years) Competitive swimmers and triathletes	For drag, the most advantageous draft distances were 0 and 50 cm behind the lead swimmer's toes, reducing drag by 21% and 20%, respectively. In the lateral design drag was significantly reduced by 6% and 7%, respectively, at 50 and 100 cm from the lead swimmer's hands	6.0±0.0

Clarys (1985)	In a quadruple approach we have suggested the ergonomics links between fundamental hydrodynamics, applied dynamics of swimming, electromyographical aspects and specific training	Fundamental and applied hydrodynamics were investigated in a Dutch Marine Ship model test station (in one person)	It was found that drag in a prone position under the water surface was greater than at the water surface, but D_A while swimming reached twice the drag values of any D_P condition. This indicates that body form has no influence on drag and propulsion	5.5±0.7
di Prampero et al., (1974)	The body drag of a swimmer was determined by adding (or subtracting) extra drag loads to (or from) swimmers moving at known speeds	The experiments were performed on 10 well-trained male college students swimming the overarm crawl at 0.55 and 0.90 m/s	The results indicate that both drag (D_A) and mechanical efficiency (e) are on the average 30 % higher than previous estimates based on the drag of passively towed subjects. The ratio, e/D_A, which is shown to be equal to the ratio of v/VO_2, provides a valuable tool in estimating swimming performance: it amounts on the average to 0.8 $kg^{-1} \times 10^{-2}$ corresponding to 58.5 ml $O_2.rn^{-1}$), independent of the speed over the range studied	5.0±00
Formosa et al., (2012)	Compare measuring D_A (MAD) and ATM	9 intermediate-level swimmers (19.7±4.4 years) completed front crawl trials with both systems during one session	The mean D_A was 82.3 N (74.0-90.6 N) for the MAD (measured at various speeds) system and 148.3 N (127.5-169.1 N) for the ATM system. These differences were attributed to variations in swimming style within each measurement system	5.5±0.7
Formosa et al., (2014)	Quantify the influence of the breathing action on net drag forces during front crawl swimming	20 elite (n=10 mal; 21.3±3.06 years; FINA point front crawl 900±69; n=10 female; 21.3±3.13 years, FINA point front crawl 917±69) national swimming team	Male demonstrated a 26 % ($p<0.001$, $d=-1.01$) in mean net drag forces between conditions. There were statistical and large differences ($p<0.001$, $d=-1.60$) in minimum net drag force between the breathing stroke side within the breathing and non-breathing conditions. Female produced a 16 % difference in overall net drag force between the testing conditions ($p=0.01$, $d=-0.55$). Minimum ($p=0.08$, $d=-0.41$) ($p=0.16$, $d=0.33$) and maximal ($p=0.15$, $d=-0.43$) net drag forces were not statistically different	6.0±00
Gatta et al., (2015)	Use the planimetric method to determine frontal area throughout the stroke cycle in the four swimming strokes as well as during "streamlined leg kicking"	10 highly trained swimmers, 6 male (21.3±0.5 years) and 4 female (20.8±0.5), competing at national level	D_A was estimated based on the average AP values, as calculated for a full cycle in each condition. D_A is the lowest in the "streamlined leg kicking" condition ($D_A=19.5v^2$), is similar in front crawl ($D_A=30.0\ v^2$), backstroke ($D_A=26.9\ v^2$) and butterfly ($D_A=28.5\ v^2$) and is the largest in the breaststroke ($D_A=37.5\ v^2$)	6.0±00
Gatta et al., (2016)	Verify whether there is a balance between the power generated by thrust forces and the power needed to overcome drag forces in front crawl swimming (using a tethered test) assessing thrust force and estimating D_A based on measures of D_P (at maximal speed)	10 front crawl high-level male swimmers (23.5±3.4 years of age); long-course 50 m and 100 m front crawl personal best times are 22.5±0.6 s and 49.5±1.4 s, respectively (representing 93±2 and 95±3% of the World Record)	No significant differences were observed between tethered swimming (Pt = 399±56 W) and D_A strength (Pd = 400±57 W), but with a strong correlation (R = 0.95, $p<0.001$). Showing that the swimmer's thrust force is close to the force needed to reduce D_A	6.0±00
Gatta et al., (2018)	Was to explore the relationships between mechanical power, thrust power, propelling efficiency and sprint performance in elite swimmers	12 elite male swimmers (22.8±3.5 years); they were part of the National Italian Team and were competing in short-distance sprint events. The long-course 50 m and 100 m freestyle personal best times are 22.5±0.6 and 49.5±1.3s	(1) by using a whole-body swimming ergometer (W'TOT) and (2) in by measuring full tethered swimming force and maximal swimming velocity. Speed-specific drag, was found to be 36.2±3.3 N. Support the capability of a whole-body ergometer to estimate W'TOT as well as the finding that propelling efficiency should be about 40% in these experimental conditions.	6.0±00
Gonjo et al., (2020)	Investigate differences in Fr efficiency and D_A between front crawl and backstroke at the same speed (Through 3D motion analysis)	10 male competitive swimmers (17.47±1.00 years), and their best records were 54.50±1.23 and 60.56±1.29 s in 100 m front crawl and backstroke, respectively	Swimmers had 8.3% longer SL, 5.4% lower SF, 14.3% smaller IdC, and 30.8% higher ηF in front crawl than backstroke in the 3D motion analysis (all $p<0.01$). Backstroke had 25% larger D_A at 1.2 m/s than front crawl ($p<0.01$) in the MRT trial	6.0±00
González-Ravé et	Determine the FSA of swimmers by means of an automated vision system.	1 regional male swimmer (age: 20 years; body mass 68 kg; height: 173 cm; training	The resistive forces that influence the swimmer in the water include form, wave drag and frictional drag, which are	6.0±00

al., (2022)		hours: 9 h per week). The swimmer was specialized in individual medley events	influenced by the swimmer's velocity, boundary layer, shape, size, and the FSA	
Hazrati et al., (2016)	Determine the reliability of the ATM method approach using a fluctuating speed tow	12 elite swimmers (5 males and 7 females, 17.7±2.9 years)	The reliability was determined using within-participant ICC within each day and between the days. This study identified that the ATM method with fluctuating speed had moderate reliability within-participant trials on values in a single day but high reliability for the average D_A values across different days (ICC=0.93). Identified that the ATM method with fluctuating speed had moderate reliability trials on values in a single day but high reliability for the average D_A values across different days	6.0±00
Hazrati et al., (2018)	Know how much uncertainty in the D_A value may be produced by each component variable using the ATM with the fluctuating velocity	12 national and state level swimmers (5 males and 7 females, 17.7±2.9 years) were recruited for this study.	The result of the uncertainty of the velocity exponent (1.8–2.6) indicated a contribution of about 6% error in D_A. The contribution of unequal power output showed that if a power changed 7.5% between conditions, it would lead to about 30% error in calculated drag	6.0±00
Hollander et al., (1986)	A system has been designed, built and tested in order to measure D_A during front crawl swimming	The male subject, who was an Olympic Games participant at Los Angeles in 1984, performed five tests on five different days	At a mean speed of 1.55 m/s the mean force was 66.3 N. The accuracy of this force measured on one subject at different days was 4.1 N. At constant speed, the mean propulsive force is equal to the opposing, D_A force	5.0±00
Kjendile et al., (2004)	Examine the influence of several explanatory factors: anthropometry, buoyancy, passive underwater torque, drag and swimming technique on the energy cost of swimming front crawl in children and adults	10 children 11.7±0.8 years 13 adults 21.4±3.7 years	Anthropometric features and active drag were responsible for the energy cost in children and adults. When normalized for body size, non-significant differences were found. Active drag at maximal speed was higher in adults [106 (68) N at a speed of 1.79 (0.05) m/s] than children [29 (9) N for 1.41 (0 ,10) m/s, p<0.001]	5.0±00
Kjendile & Stallman, (2008)	Compare drag in swimming children and adults, quantify technique using the TDI, and use the F_r to study whether children or adults reach hull speed at maximal velocity (F_r)	9 children 11.7±0.8 years 13 adults 21.4±3.7 years	The children (C_{DA}=0.66±0.14) had significantly lower D_A factor compared with the adults (C_{DA}=0.84±0.46) Technique drag index could not detect any differences in between the two groups, owing to the adults swimming maximally at a higher F_r, increasing the wave drag, and masking the effect of better technique	6.0±00
Kolmogorov & Duplishcheva, (1992)	Compare the time of the same distance swum with and without an added resistance, under the assumption of an equal power output	73 swimmers (competitive level)	D_A in females ranged from 65.51 to 37.79N in backstroke, 93.56 to 45.19 N in breaststroke, 83.04 to 37.78 N in dolphin and 69.78 to 31.16 N in the front-crawl. In Males ranged from 146.28 to 46.36 N in back-stroke, 176.87 to 55.61 N in breaststroke, 156.09 to 46.95 N in dolphin and 167.11 to 42.23 N in front-crawl	6.0±00
Kolmogorov et al., (1997)	Describe the magnitudes of D_A, C_D, and power output in the four swimming strokes for athletes of different performance levels, sexes, and ages at maximal swimming velocities	This research was conducted over a 5 year period leading up to the 1992 Olympic Games in Barcelona. The subjects included 310 females and 487 males ranging in age from 10 to 28 years	In all swimming strokes at the maximal absolute velocity, men experienced greater C_D well as much greater power outputs (virtually twice as much) than women. Within each stroke, the most important factor for reducing D_A appeared to be individual biomechanical technique	6.0±00
Kolmogorov et al., (2021)	Determine the main biophysical (energetic and biomechanical) reasons for the observed differences in maximal swimming velocity between the different competitive swimming techniques	8 elite swimmers (4 females and 4 males), each of whom specialized in different swimming techniques and ranked among the top 10 in the world in the 100 m event in their swimming specialty	At the last stage of the test, in all techniques, men demonstrated higher values of metabolic power (P_{ai}=3346–3560 W) and higher mechanical efficiency (e_g=0.062–0.068) than women (P_{ai}=2248–2575 W; e_g=0.049–0.052). The main reason for the differences in maximal swimming velocity between different techniques is the frontal component of D_A force	6.0±00
Lyttle et al., (1999)	A towing device was designed to quantify drag experienced by swimmers at predetermined velocities and depths	A servo controlled mechanical winch was used to tow the swimmers along the length of a 25m pool and a pulley arrangement allowed the towing forces to be essentially horizontal at the required depth	Initial results indicate that the towing device effectively and reliably calculated the drag forces experienced by swimmers in a prone, streamlined position at velocities between 1.6 and 3.1 m/s. The required depth for towing could also be accurately established. The towing device will enable reliable	5.0±1.4

			information on the swimmer's D_A to be collected	
Lyttle et al., (2000)	Establish an appropriate speed for initiating underwater flutter kicking, as well as the most effective gliding position and kicking technique to be applied after a turn	16 experienced adult male swimmers (19.3±2.1 years). Swimmer's experience (5.3±1.8 years) and national competition (3.8±2.0 years)	Demonstrated an optimal range of speeds (1.9 to 2.2 m/s) at which to begin underwater flutter kicking to prevent energy loss from excessive D_A. There appears to be no significant advantage in using one streamlining technique over another or in using one kicking style over another	6.0±00
Marinho et al., (2010a)	Assess the effects of 8-weeks of training on D_A in young swimmers of both sexes	8 girls and 12 boys belonging to the same swimming team and the previous two seasons with regular competitive participation	After 8 weeks of training, mean D_A (drag force and drag coefficient) decreased in girls and boys (girls: 29.18±15.24 N vs. 27.50±10.36 N, 0.35±0.23 vs. 0.30±0.09; boys: 38.30±17.49 N vs. 36.35±13.12 N, 0.33±0.11 vs. 0.31±0.09; $p>0.05$). No significant differences were found between the two trials (34.66±16.84 N vs. 32.81±12.60 N, 0.34±0.16 vs. 0.31±0.09). These differences corresponded to a 5.34±0.46 % and 8.82±0.83 %	6.0±00
Marinho et al., (2010b)	Study was to assess the effects of 8 weeks of training on D_A in young female swimmers	8 females age group swimmers belonging to the same swimming club with good competition level (11.63±0.52 years old)	After 8 weeks of training, mean D_A decreased, although no significant differences were found between the two trials (29.18±15.24 N vs. 27.50±10.36 N). No significant differences were observed in swimming velocity between the two trials (1.23±0.13 N vs. 1.25±0.15 N)	6.0±00
Masset et al., (1999)	Analyze the 3D analysis of the backstroke style and the views were digitally broken down frame by frame in order to obtain smoothed 3D trajectories for the hip and wrist	32 male swimmers were filmed during the National and International Championships 100m backstroke event using two underwater camcorders	The 3D hand movement allowed the swimmer to create lift and drag forces to propel the body forwards. Small deviations of the body were observed, albeit with significant individual variations, along the lateral and vertical axes in reaction to the wrist action. These unnecessary body displacements may induce an increase in D_A	5.5±0.7
Morais et al., (2011)	Compute and validate TTSA area estimation equations to assess the swimmer's drag force in both sexes	264 subjects (152 males (between 10-32 years) and 112 females (between 9-27 years)). All subjects were competitive swimmers with regular participation	No significant differences between assessed and estimated mean TTSA. Coefficients of determination for the linear regression models between assessed and estimated TTSA were R2 = 0.39 for males and R2 = 0.55 for females. More than 80% of the plots were within the 95% interval confidence for the Bland-Altman analysis in both sexes	6.0±00
Morais et al., (2012)	Develop a structural equation model (i.e., a confirmatory technique that analyzes relationships among observed variables) for young swimmer performance	114 subjects (73 boys and 41 girls of mean age of 12.31±1.09 years and Tanner stages 1–2) were evaluated	Main data showed that swimming performance is dependent on SI (an efficiency estimator) and this in turn on the *dv*, SL, AS and D_A. Swimming efficiency improvement is related to a decrease in the *dv* and an increase of the SL and AS. The increase in the D_A is a result of the increase in swimming velocity. For boys D_A ranged between 11.81 N and 73.15 N. For girls, D_A varied between 16.49 N and 54.59 N	6.0±00
Morais et al., (2014)	Model a latent growth curve of young swimmers' performance and biomechanics over a season	30 young swimmers (14 boys: 12.33±0.65 years, 284.85±67.48 FINA points at the short-course meter 100 m front crawl; and 16 girls: 11.15±0.55 years, 322.56±45.18 FINA points at the short-course meter 100 m front crawl)	Latent growth curve modeling showed a high inter- and intra-subject variability in the performance growth. Sex had a significant effect at the baseline and during the performance growth. In each evaluation moment, different variables had a meaningful effect on performance (M1: D_A, $\beta=-0.62$; M2: D_A, $\beta=-0.53$; M3: η_p, $\beta=0.59$; M4: SF, $\beta=-0.57$; all $p<0.001$)	6.0±00
Morais et al., (2015)	Apply a new method to identify, classify, and follow up young swimmers, based on their performance and its determinant factors over a season, and to analyze the swimmers' stability over a competitive season	33 young swimmers (11.8±0.7 years; 15 boys (12.3±0.6 y); 18 girls (11.7±0.9 y); Tanner stages 1–2 by self-report)	Cluster 3 was characterized by high C_D (M1); SI, ηp, and v (M2); and chest perimeter, AS and average performance. Stepwise discriminant analysis revealed that 100%, 94%, and 85% of original groups were correctly classified for the 1st, 2nd, and 3rd ($0.11\leq \Lambda \leq 0.80$; $5.64\leq \chi2 \leq 63.40$; $0.001< p \leq 0.68$). Membership of clusters was moderately stable over the season	6.0±00
Morais et al., (2016)	Compute a swimming performance confirmatory model based on biomechanical parameters	100 young swimmers (12.3±0.74 years; 49 boys: 12.5±0.76 years; 51 girls: 12.2±0.71 years; both sexes	69% of the performance of young swimmers is explained through the model (strength on dry land, power in water and kinematic variables). Dry-land strength has a positive and large effect on the in-water power	6.0±00

		in Tanner stages 1–2 by self-report)	output, and in turn on the stroke mechanics (v and ηp), thus enhancing the performance, where D_A is included in the predominant factor	
Morais et al., (2020a)	Analyse the detraining process that occurs during a season break, and its influence on the performance, anthropometrics, and biomechanics of young swimmers	54 young swimmers (22 boys: 12.79±0.71 years; 32 girls: 11.78±0.85 years; maturation stage: Tanner 1–2)	The C_{DA} increase between M1 and M2 may reflect the swimmers' need for a higher physiological power to overcome drag at a given swim velocity. Despite the v increase, girls did decrease slightly for the D_A (D_A t-test=−0.77 (0.447) N). The C_{DA} increased between the moments (boys and girls)	6.0±00
Morais et al., (2020b)	Compare D_A calculation between a single land-based measurement of FSA and in-water FSA measures obtained at key events of the arm pull and compare mechanical power variables computed based on these two approaches	17 good national level swimmers (11 male; 6 female; 16.15±0.94 years). FSA was measured using the Velocity Perturbation method	Besides the FSA, swim speed also changes during the crawl arm pull, having a significant effect on the D_A measure and on the mechanical power and total input power variables. The FSA was higher than when assuming a nonvariation ($p<0.001$) and D_A was also significantly higher than when assuming a nonvariation ($p=0.002$)	6.0±00
Morais et al., (2021)	Classify, identify and follow-up young swimmers' performance and its biomechanical determinants during two competitive seasons and analyze the individual variations of each swimmer	30 young swimmers (14 boys: 12.70±0.63 years; 16 girls: 11.72±0.71 years)	The performance improved between moments of assessment in all clusters (cluster 1 ("talented"), cluster 2 ("proficient"), and cluster 3 ("non-proficient")). The hydrodynamic variables (D_A and C_{DA}) increased, but this fact may be related to the increase in swimming velocity, which is directly related to the drag	6.0±00
Moreira et al., (2014)	Analyse the effect of growth during a summer break on biomechanical profile of talented swimmers	25 talented swimmers including 12 boys (12.8±0.9 years; 50.09±10.13 kg) and 13 girls (12.0±0.9 years; 49.42±7.47 kg)	The stroke frequency, D_A, and C_D remained unchanged. When controlling the effect of growth, no significant variation was determined on the biomechanical variables. Young talented swimmers present biomechanical improvements after a 10-week break, which are mainly explained by their normal growth, inclusive for D_A (Pearson correlation 0.40 ($p=0.06$) to 0.52 ($p=0.08$)) and C_{DA} (0.39 ($p=0.06$) to -0.07 ($p=0.55$))	6.0±00
Moriyama et al., (2021)	Investigate the effects of jammer-type racing swimsuits on swimming performance during arm-stroke-only (pull) and whole-body stroke (swim) in 25 m front-crawl with maximal effort	12 well-trained male collegiate swimmers (21.3±1.4 years, 512.8±83.1 FIFA points)	Jammer-type racing swimsuits would improve sprint performance to accompany with increase in the maximal swimming velocity compared with the conventional training swimsuit. Although it was not possible to identify the factors that improved the swimming velocity, the drag may be an explanatory factor. However, the results do not confirm the swimsuit's function of supporting the improvement to D_A ($p>0.124$)	6.0±00
Narita et al., (2017)	Develop a new method for evaluating the drag in front-crawl swimming at various velocities and at full stroke (MRT-method)	6 male competitive swimmers (20.0±1.0 years and 52.6±0.6 seconds performance time at 100 m front crawl)	D_A was estimated in five-stages for velocities ranging from 1.0 to 1.4 m/s. D_A (D_A =32.3 v3.3, N=30, $R^2=0.90$) was larger than D_P (D_P=23.5 v2.0, N=42, $R^2=0.89$) and the variability in D_A for the two swimmers was 6.5% and 3.0%	6.0±00
Narita et al., (2018a)	Examine the effect of leg kick on the resistance force in front-crawl swimming	7 male competitive swimmers (20.0±0.9 years and and 115.5±3.0 seconds performance time at 200 m front crawl)	For both the WS and AS at both swimming velocities, C_{DA} was found to be about 1.6–1.9 times larger than in passive conditions. In contrast, although leg movement did not cause a difference in drag coefficient for front-crawl swimming, there was a large effect size (d=1.43) at 1.3 m/s	6.0±00
Neiva et al., (2021)	Analyze the effects of a swimming training mesocycle in master swimmers' performance and D_A	22 master swimmers (39.87±6.10 years and 6.47±5.41 years of experience). Male (n=16) and female (n=6) swimmers	Maximal, mean and minimum front crawl speeds improved from pre- to post-training and the speed decrease along the 25 m test lowered after the training period (82.5±76.3%, $p=0.01$). The training mesocycle caused a reduction in the D_A at speeds corresponding to 70% (5.0±3.9%), 80% (5.6±4.0%), and 90% (5.9±4.0%), but not at 100% (5.9±6.7%), of the swimmers' maximal exertions in the 25 m test	6.0±00
Papic et al., (2020)	Determine the influence of torso morphology on maximal instantaneous	15 Scottish national and international level male swimmers (7 sprint	Indentation at the waist and curvature of the buttocks may result in greater drag force and influence swimming performance.	6.0±00

	hydrodynamic resistance in front crawl swimming	specialists (18.3±2.3 years) and 8 distance specialists (17.5±2.5 years)). 10 male national level Portuguese swimmers (17.47±1.00 years)	Instantaneous C_D were significantly greater than those derived from front crawl D_A analysis throughout the literature. Differences in drag coefficients may be due to the assumption used in D_A methodologies, that a swimmer's velocity remains constant throughout the stroke cycle, rather than fluctuating	
Pendergast et al., (1977)	Body drag and mechanical efficiency were measured from the relationship between extra oxygen consumption and extra drag loads	42 male (16-24 years) and 22 female (17-21 years) competitive swimmers (college level)	Using speeds ranging from 0.4 to 1.2 m/s. Drag increased from 3.4 (1.9) kg at 0.5 m/s to 8.2 (7.0) kg at 1.2 m/s, with Drag of women being significantly less ($p<0.05$) than that of men. Drag and efficiency of swimming was shown to be identical to the directly measured energy cost of swimming one unit distance, VO_2/Drag, and was independent of the velocity up to 1.2 m/s.	5.5±0.7
Peterson Silveira et al., (2019)	Compare different methods to assess the arm SE, identify biophysical adaptations to swimming on the MAD System and the main biophysical predictors of maximal swimming speed in the 200 m front crawl using the arms only	14 national level competitive swimmers (eight males, six females, age: 17.3±2.2 years)	Both methods to assess on the MAD System differed ($p<0.001$) from the expected values for this condition ($\eta F=1$), with the speed-based method providing the closest values ($\eta F \sim 0.96$). The main assumption of this method is that the D_A and the effective force applied by the hand are the same for a given constant speed. The speed-based method provides confirm that swimming performance depends on the balance of biomechanical and bioenergetic parameters	6.0±0.0
Poizat et al., (2010)	Evaluate the usability of the Measuring D_A (MAD) system, a technical device for biomechanical evaluation and performance analysis	3 international male swimmers volunteered. Age, experience, and time on 100m front crawl (in 50-m pool) were (21.3±1.2 years, 10.7±2.1 years, 50.9±1.2 seconds)	The results are presented in two stages: (a) the concerns and modalities of using, and (b) use sensations. One of the most important results was that these components changed according to the swimmer's speed when using the MAD system	5.5±0.7
Ribeiro et al., (2016)	Verify the use of the new AquaTrainer® respiratory snorkel lead to an increase of front crawl hydrodynamic drag and whether the constraint of using an adapted turning technique influences its corresponding turning time	12 national-level swimmers (age: 22.2±6.3 years, training background: 7.6±5.4 years and training frequency: ≥7 units per week, percentage of the 100m world record: 83.16±16.42%)	Front crawl swimming with snorkel using the open turn implied an increase in turning time of 14.2 and 5.1% than the tumble turn and open turn without the apparatus ($p<0.01$). AquaTrainer® snorkel does not lead to increased D_A during forward tracking (performed at various speeds) and the metabolic energy required to overcome drag will not be affected	6.0±0.0
Ribeiro et al., (2017)	Examine how high- and low-speed swimmers organize biomechanical, energetic and coordinative factors throughout extreme intensity swim	16 male swimmers were divided in two performance level groups (21.1±3.3 vs. 18.6±1.6 years of age, 115±4% vs. 124±3% of 100-m front crawl world record time for high- (n=8) and low-speed (n=8)	Performing at extreme intensity led better level swimmers to achieve superior speed due to higher power and propelling efficiency, with consequent ability to swim at higher stroke frequencies. This imposes specific constraints, resulting in a distinct IdC magnitude and profile between groups and in turn a smaller C_D, although D_A is naturally larger	6.0±0.0
Schreven et al., (2013)	Determine the effect of inter-pad distance on D_A at a given speed	11 competitive swimmers (20.0±6.2)	Variation of 16% in inter-pad distance (14% change in stroke frequency) revealed no significant difference in calculated D_A between different inter-pad distances and a low (<5%) average coefficient of variation over different inter-pad distances was found. D_A was 23.60 N (95% CI 22.19, 25.02) greater at 1.55 m/s compared to 1.25 m/s	6.0±0.0
Seifert et al., (2010)	Examine how a combined group of national and regional swimmers organized their stroke (i.e., their inter-limb coordination and their power output application) to increase v, and more particularly how the national swimmers changed their coordination when swimming at higher speeds	14 French male swimmers (7 national swimmers 21.9±4.2 years, training 20.0±1.0 h per week and had 11.6±2.5 years of practice; 7 regional swimmers 21.7±3.1 years, training 9.4±4.3 h per week and had 8.0±4.3 years of practice)	Both groups increased IdC and hand speed (u) and applied greater Pd to overcome D_A ($F(7.96)=30.92$, $p<0.05$) with speed increases ($p<0.05$). The regional swimmers exhibited a higher u and lower SI, IVV, and v2/u2 compared to national swimmers ($F(1.96)=5.77$, $p<0.05$ and Pd $F(1.96)=7.81$, $p<0.05$), which revealed lower effectiveness to generate propulsion, suggesting that technique is a major determinant of swimming performance	6.0±0.0

Seifert et al., (2015)	Examine the relationships between the IdC and D_A assuming that at constant average speed, average drag equals average propulsion	20 French national volunteer male front-crawl swimmers (21.6±2.4 years, mean year of practice: 11.4±3.4)	IdC was linked to D_A by linear regression ($IdC=0.246$; $R^2=0.88$, $p<0.05$); swimmers switched from catch-up to superposition coordination mode at a speed of similar to 1.55 m/s where average D_A is similar to 110 N. Inter-individual analysis showed that high IdC did not relate to a high propulsive efficiency suggesting an individual optimization of force and power generation is at play to reach high speeds	6.0±0.0
Sharp & Costill, (1989)	Assess the effect of shaving body hair on physiological responses to free and tethered breaststroke swimming and to examine the effect on velocity decay during a prone underwater	9 male collegiate swimmers (21.0±1.0)	Removing body hair significantly reduced the rate of velocity decay during a prone glide after a maximal underwater leg push-off. It is concluded that removing body hair reduces D_A, thereby decreasing the physiological cost of swimming	5.5±0.7
Silva et al., (2019)	Conduct a multivariate analysis of young swimmers' sprint performance to determine which are the key variables when analyzing the effect of sex and skill	23 male (15.7±0.8 years) and 26 female (14.5±0.8 years) swimmers at the national level in the postpubertal maturational stage (Stage 4).	Biomechanical variables play a crucial influencing factor in sprint performance (at these ages), with swimmers focusing on performing better and more efficient technique (through better SI and IVV). Furthermore, sex proved to be an important factor influencing sprint performance.	6.0±0.0
Silva et al., (2007)	Examine the effects of 21 days of creatine supplementation (CS) on swimming performance on performance related hydrodynamic variables and on body composition in national junior female swimmers, during the last period of training preparation	16 healthy competitive national level female swimmers (CS group n=8 and placebo supplementation (PL) group n=8, 16.3±1.8 years for CS group and 15.7±1.2 years for PL group)	Significant differences were observed in hydrodynamic values: the CS group showed a significant reduction (≈25%), in D_A force or F_d, C_x and power output values, when comparing pretest with post-test. These data suggest that 21 days of CS produced significant effects on gross and/or propelling efficiency during swimming in female athletes. However, CS did not influence performance, body weight and body composition	6.0±0.0
Silveira et al., (2019)	Compare different methods to assess the arm SE and to identify biophysical adaptations to swimming on the MAD System and the main biophysical predictors of maximal swimming speed in the 200m front crawl using the arms only	14 national level competitive swimmers (eight males, six females, 17.3±2.2 years)	Both methods to assess SE on the MAD System differed (≈4%, $p<0.001$). In the free-swimming condition, the power-based, speed, and paddle-wheel efficiencies were significantly different (≈39%, $p<0.001$). Although all methods provided values within the limits of agreement, the speed-based method provided the closest values to the "actual efficiency"	6.0±0.0
Stosic et al., (2021)	Examine the role of segmental, kinematic and coordinative parameters on the swimming velocity during the pre-transition and transition phases	30 national level male swimmers (16.80±1.44 years) with a personal best time in the 100 m front crawl, backstroke, butterfly or breaststroke events within the 85% of world record (86.03±2.34%)	These results suggest that the body position and coordinative swimming parameters (apart from kicking or stroking rate and length) have an important influence on the transition performance, which depends on the swimming strokes and directly influences D_A and C_D	6.0±0.0
Takagi et al., (1999)	Measure D_A, which is dynamic drag acting on a self-propelling swimmer in water	4 collegiate skilled swimmers (21.0±0.8)	Was possible to measure D_A more precisely than before, and to obtain the experimental equation that predicted the D_A within a range of Reynolds number equaled the actual swimming velocity	5.5±0.7
Toussaint et al., (1988a)	The propelling efficiency (ep) of front-crawl swimming, by use of the arms only, was calculated. To measure mechanical power (P_o) and drag (D_A) by using a technique developed in laboratory. To report for the first time experimental determinations of ep in swimming humans	4 male swimmers competing at international and national levels (mean: 22.3 years and 53.8 time of 100 m front crawl)	$ep = D_A/(D + P_k{}^*) = D_A/P_o$. ep was found to range from 46 to 77%. Total efficiency, defined as the product of mechanical and propelling efficiency, ranged from 5 to 8%. * kinetic energy of masses of water (P_k)	6.0±0.0
Toussaint et al., (1988b)	Analyze D_A related to velocity in male and female swimmers. Propulsive arm forces were measured during front crawl swimming using arms only	32 male and 9 female swimmers of good competitive level	It was found that D_A force is related to the swimming velocity v raised to the power 2.12±0.20 (males) or 2.28±0.35 (females). Differences in drag force and coefficient of drag between males and females (drag: 28.9±5.1 N, 20.4±1.9 N, drag coefficient: 0.64±0.09, 0.54±0.07 respectively) are	6.0±0.0

			especially apparent at the lowest swimming velocity (1 m/s), which become less at higher swimming velocities	
Toussaint et al., (2002)	Study the effect on drag of a Speedo Fast-skin suit compared to a conventional suit. The total D_A when swimming in the body Fastskin™ was compared with that evoked when wearing conventional swimwear.	13 subjects (6 males, 7 females) swimming at different velocities between 1.0 and 2.0 m/s	The D_A force was directly measured during front crawl swimming using a MAD system. For a range of swimming speeds (1.1, 1.3, 1.5 and 1.7 m/s). On a group level, a statistically non-significant drag reduction effect of 2% was observed for the Fastskin™ suit ($p=0.31$). Therefore, the 7.5% reduction in drag claimed by the swimwear manufacturer was not corroborated	6.0±0.0
Toussaint et al., (2004)	Determine whether the MAD and VPM system measure D_A	6 top-level international competitive swimmers from the swimming team TZA (20.7±3.7). The mean performance for the 100m time(s) was 52.0±2.1	The average drag for the VPM tests (53.2 N) was statistically significant and different from the D_A for the MAD-test (66.9 N). The regression of the relative difference in force (MAD vs VPM) on the relative difference in power was: %Deltadrag=1.898 x %Deltapower -4.498, $R^2=0.88$. This suggests that the major part of the difference in D_A values is due to a non-equal power output in the 'free' relative towing trial during the VPM-test	6.0±0.0
Toussaint & Vervoorn, (1990)	Describe a new training device derived from the MAD system for front crawl swimming	11 (8 male and 3 female, 18.50±3.30); Training group: 11 (8 male and 3 female, 18.40±2.10)	Despite the fact that training time and volume were equal, the training group showed a significantly greater improvement in force (from 91 to 94 N, 3.3%), velocity (from 1.75 to 1.81 m/s; 3.4%) and power (from 160 to 172 W, 7%) as measured on the MAD system, and an increase in distance per stroke in free swimming.	6.0±0.0
Van der vaart et al., (1987)	Calculate the drag on moving swimmers from direct propulsive arm force measurements (MAD System)	12 male swimmers	The mean propulsive force at a velocity of v=1.48 m/s was shown to be 53.2±5.8 N (two to three times smaller than other studies for D_A) which is in agreement with the values reported for D_P in a swimmer (towed on MAD System) that is not moving. In this study, discrepancies in D_A measurements are discussed	5.0±0.0
Vilas-Boas et al., (2010)	Assess and to compare the hydrodynamics of the first and second gliding positions of the breaststroke underwater stroke used after starts and turns	12 national-level swimmers (6 males and 6 females, respectively 18.2±4.0 and 17.3±3.0 years)	For the same gliding velocities (1.37±0.124 m/s), Drag force and the swimmers' cross-sectional area and C_D values obtained for the first gliding position are significantly lower than the corresponding values obtained for the second gliding position of the breaststroke underwater stroke (31.67±6.44 N vs. 46.25±7.22 N; 740.42±101.89 cm^2 vs. 784.25±99.62 cm^2 and 0.458±0.076 vs. 0.664±0.234, respectively)	6.0±0.0
Xin-Feng et al., (2007)	Develop a simple and convenient device to measure the D_A at maximal velocity based on the equal power output assumption	6 swimmers of national standard (3 males, 3 females)	For the males, the mean D_A ranged from 48.57 to 105.88 N in the front crawl and from 54.14 to 76.37 N in the breaststroke. For the females, the mean D_A ranged from 36.31 to 50.27 N in the front crawl and from 36.25 to 77.01 N in the breaststroke. The device provides a useful method for measuring and studying D_A.	6.0±0.0
Zamparo et al., (1996)	Investigate whether the observed increases of unit of distance with underwater torque during front crawl swimming were due to an increase of D_A, a decrease of drag efficiency or both	8 male elite swimmers (21.1±1.36 years) at two submaximal speeds (1.00 and 1.23 m/s)	Underwater torque increased by 73% and that unit of distance, D_A and drag efficiency increased linearly with underwater torque. The increase of unit of distance between the two extremes was intermediate (≈20%) between that of D_A (≈35%) and of drag efficiency (≈16%). Thus, the actual strategy implemented by the swimmers to counteract underwater torque, was to tolerate a large increase of D_A	5.0±0.0
Zamparo et al., (2009)	Investigate the role of trunk incline and projected frontal area in determining drag during active/passive measurements	6 elite college US swimmers (20.0±1.3 years) 25 subjects (14 male and 11 female swimmers, respectively 23.9±2.4 and 22.5±2.2 years)	Both projected frontal area and trunk incline were found to decrease with the swimming speed ($D_A/v^2=67.7-22.2 \times v$, $R=0.447$, $n=60$, $p<0.001$) whereas the drag coefficient was found to be unaffected by the swimming speed. These data suggest that speed specific drag depend essentially on aprojected frontal	6.0±0.0

area. This suggest, at a given speed, that D_A is larger than D_P

D_A – active drag; D_P – passive drag; C_D – coefficient of drag; C_{DA} – coefficient of active drag; IdC – index of coordination; F_r – froude number; F_d – active drag force; C_x – hydrodynamic coefficient; P_{ai} – metabolic power (power input); P_k - mechanical power to transfer; AP – pitch angle; ICC - intra-class correlation coefficients; SL—stroke length; SF - stroke frequency; SI—stroke index; SE - stroke efficiency; WS – whole stroke; *dv*—speed fluctuation; AS—arm span; IVV – intra-cyclic velocity variations; TDI – technique drag index; SPH – coupled biomechanical-smoothed particle hydrodynamics; FSA - frontal surface area; TTSA – trunk transverse surface; MAD – measuring active drag; ATM – assisted towing method; MRT – residual thrust measured values; VPM – speed perturbation method; AIS – assisted towing method; SD – one standard deviation.

Discussion

The aim of this study was to perform a systematic narrative review on the up-to-date body of knowledge on D_A and its components through numerical and experimental methods. In the studies that used numerical methods for the D_A analysis, it was found that the main focus was to: (1) confirm whether the drag measured the same force throughout the entire path; (2) verify the variation within the stroke cycle or between stroke cycles. Overall, the studies that focused on the experimental methods to assess D_A tended to: (1) present the comparison between the determining factors of performance; (2) emphasize the comparison between the drag variation at different swimming speeds and between sexes and age groups.

Numerical methods – D_A

Most studies were focused on the front crawl stroke for submaximal speeds (Cohen, Cleary & Mason, 2012; Cohen et al., 2018; Yuan et al., 2019). It was found that the ratio of arm thrust to leg thrust increases with a higher stroke rate (Cohen et al., 2018). However, the attempt at specificity is also evident, i.e., they investigate specific movements such as kicks and arm strokes (cycles). Another study also analyzed the effects of buoyancy during swimming and the drafting as a parameter performance for competition (Cohen et al., 2014). Additionally, the authors observed that at different flow velocities, the hydrodynamic coefficients considered were not constant, knowing that the variation for different hand positions was examined for different phases of the path (Cohen et al., 2018). Regarding D_A using numerical methods (Table 2), it was noted that the coefficient of variation (CoV) decreases from 4.8% at the lowest frequency to 3.9% at the highest frequency, indicating that velocity fluctuations decrease with the stroke rate (Cohen et al., 2018). It also highlights the asymmetries in the duration of the different phases of the strokes. The right arm had a 33% shorter impulse period and a 14% longer recovery period than the corresponding periods of the left arm. The duration of the traction phase was similar for both arms (Cohen et al., 2018). There are differences between the use of the underwater flutter kick over the large/slow kick or small/fast kick at 2.18 m/s (Keys & Lyttle, 2007), confirming that the D_A, in relation to all these variables, is entirely influenced by the great variation between asymmetries, type of stroke, type of kick, and considering the type of style the swimmer is performing.

During the movements, vortex structures are generated by the arms, which then pass along the body towards the movement of the legs (using a female swimmer at submaximal speed in front crawl). These structures dissipate quickly due to the high-frequency kicking of the legs. There are earlier and more recent references (Cohen et al., 2018; Cohen et al., 2020) that suggest that generated vortices can be used to increase propulsion through vortex recapture. Another study that determined the pitching effects of buoyancy during all competitive swimming strokes (front crawl, backstroke, breaststroke, and butterfly) with a male swimmer and a female swimmer at constant submaximal speed verified that the average thrust torque tended to increase in the legs and decrease in the head (Cohen et al., 2014). However, the instantaneous torque had an opposite effect during part of the throttle stroke. In addition, the alternating techniques (front crawl and backstroke) showed smaller variations in the positions of the center of mass, thrust torques and positions of the center of thrust (Cohen et al., 2014). The simultaneous techniques (butterfly and breaststroke) showed greater variations in buoyancy torques, directly influencing the swimmer's ability to maintain a horizontal inclination to perform the strokes. This helps athletes swim efficiently by minimizing their frontal areas and the consequent pressure drag (Cohen et al., 2014). The CoV values were moderate for front crawl (53% for women and 26% for men, respectively, this order will be used from now on) and backstroke (52% and 28%), with female values being approximately twice than those of males. The CoV values for butterfly (132% and 133%) and breaststroke (130% and 127%) were significantly higher than for the other strokes. The CoV is higher for strokes with synchronized limb movement. The CoV, and consequently D_A, change depending on the movement or swimming phase, being different between kicks and strokes (Cohen et al., 2015). Regarding dolphin kicks, it was observed that the CoV of swimming velocity remains small (7-9%) in experiments with dolphin kicks even when the frequency increases. The amplitude of velocity fluctuations increases, which turns out to be much lower than other intracycle simulations (28-59%). The extension kick proved to be more important than the flexion kick (extension can also be known as down in prone swim and up in dorsal swim) for generating momentum (Cohen et al., 2012). The study by Keys and Lyttle (2007) also demonstrated that it is beneficial to use the underwater flutter kick over the large/slow kick or the small/fast kick using the CFD method.

In all techniques, but mostly in front crawl, swimmers should focus on maximizing their leg extension (it can be called the whiplash effect), as this generates most of the impulse (Cohen et al., 2012). Additionally, they should focus on decreasing D_A, even knowing that these values change according to important multivariable and that they derive from the variation of swimming along the swimming path. For example, the full dolphin kick strikes a balance between minimizing drag and maximizing thrust while minimizing the physical effort required of the swimmer (Cohen et al., 2012). The periods before course reversals correspond to the maximum drag forces in the direction of the current, so swimmers should be aware of rapid reversals of direction (turns). After starting and turning, increasing stroke frequency (SF) automatically results in a linear increase in speed. All these recommendations described can be useful to optimize the swimmer's stroke technique (Cohen et al., 2012). It can be assumed that studies with numerical methods have a higher percentage of studies variability (83.3% focus on the front crawl technique), despite a low number of articles that consider D_A. Most studies that focus on front crawl try to evaluate multivariable (strokes, kicks, and stroke frequency), but always at constant speed (submaximal). In a way, studying the drag while considering these variables has become crucial in these studies. In butterfly, studies focused on the analysis of underwater dolphin kicks concluded that cases of higher kick frequency produced higher peaks of both thrust and drag, as already mentioned in a study by the same author that focuses on the front crawl technique. The extension kick proved to be more important for generating momentum than the flexion kick. The only study that showed a greater range of study was the one by Cohen et al., 2014 in which they compared all swimming techniques for a constant submaximal speed. The authors confirmed that the variation in buoyancy torque is much greater during breaststroke and butterfly than during front crawl and backstroke, having a peak of D_A in this phase compared to the other techniques.

It should be noted that numerical methods that measure D_A have some limitations. A main limitation of the laser body scanned method is that the volume enveloped by the triangular surface mesh is assumed to be of uniform density on the entire swimmer's internal volume, which requires a very detailed reproduction of the swimmer's body, as well as specific kinematics to be accurate (Cohen et al., 2012; Cohen et al., 2015). Another limitation is the approximation of the free surface as a horizontal plane (Cohen et al., 2012; Cohen et al., 2015). Swimming involves rapid accelerations and decelerations of the limbs and the estimates obtained are highly limited (Cohen et al., 2015). Regarding the numerical methods, the body position was limited to a single angle to prevent the swimmer's model from deviating from its course, which ended up conditioning the trajectory, and the results obtained (Cohen et al., 2020). These limitations constitute a solid basis to be considered in future studies (Cohen et al., 2015; Yuan et al., 2019).

Experimental methods – D_A

Effects of D_A on elite/adult swimmers

Historically, D_A was first measured in adult swimmers (e.g., di Prampero et al., 1974; Kolmogorov et al., 1997). Overall, studies noted that drag and C_D are about 1.5-2 times greater in D_A than in passive conditions (di Prampero et al., 1974; Kolmogorov et al., 1992). In addition, such studies confirmed that better swimming technique reduced D_A essentially due to reduced C_D. Indeed, Kolmogorov et al. (1997) supported the idea that elite swimmers have a greater ability to reduce D_A than non-elite swimmers. More recently, Neiva et al. (2021) analyzed the effects of a swimming training mesocycle on the performance and D_A of master swimmers in front crawl. The authors concluded that there is an improvement in the performance of master swimmers after four weeks of aerobic training. This also resulted in the reduction of D_A while swimming mainly at submaximal speeds. Therefore, based on the literature, it can be stated that technical training plays a key role on reducing D_A. Nonetheless, adult/elite swimmers tend to present greater D_A

and power needed to overcome drag, especially when the competitive level increases (Kolmogorov, Vorontsov & Vilas-Boas, 2021; Morais et al., 2020a; Seifert et al., 2010; Takagi et ai., 1999; Toussaint et al., 2004; Zamparo et al., 1996; Zamparo et al., 2009). Furthermore, it is known that there are several variables that can directly influence the drag of a swimmer, as expressed in equation (3). Such variables are also dependent on external variables and in adults become even more important (Kjendlie et al., 2008; Kolmogorov et al., 1997). Adult/elite swimmers tend to have a larger FSA and a fastest swimming speed than other age groups (Gatta et al., 2015; González-Ravé et al., 2022; Kolmogorov et al., 2021). Body position may also affect the hydrodynamic position and, consequently, D_A. For example, Formosa et al. (2014) aimed to quantify the influence of the breathing action on D_A during swimming. This variation is reported to be large when compared to non-breathing, with a 16% to 26% difference in drag force during swimming. The simple act of breathing changes $D_{A,}$ so this variable must also be considered. Others aimed to study D_A in a completely different way, examining relationships between IdC and D_A assuming that at a constant speed, the average drag is equal to the average propulsion, expressing the idea presented in the equation (1) (Seifert et al., 2015). In front crawl swimmers, changes in inter-arm coordination were linked to changes in resistance forces when swimming at different speeds. A significant and positive linear regression between IdC and D_A was observed (Seifert et al., 2015). Overall, adult/elite swimmers present greater values of D_A, mainly based on the assumption that they generate a greater metabolic power and mechanical power (Gatta et al., 2016; Kolmogorov et al., 2021).

Effects of D_A on young swimmers

Active drag has been largely studied in young swimmers over the last decade, specifically in front-crawl (Barbosa et al., 2010b; Kjendile et al., 2004; Marinho et al., 2010a; Morais et al., 2012; Morais et al., 2021). In studies on this topic, the authors noted that the best performers were also those with the highest D_A and C_{DA} (Barbosa et al., 2019; Morais et al., 2015). As expressed in equation (2), drag variables are highly dependent on swimming velocity and FSA. This indicates that bigger and faster swimmers are more likely to be under more drag (Barbosa et al., 2019; Morais et al., 2021; Silva et al., 2019). For example, top performers in freestyle sprinting events (front-crawl swim) not only had faster swimming velocity and better kinematics and swimming efficiency but also higher D_A (Barbosa et al., 2013; Barbosa et al., 2019; Ribeiro et al., 2017). Thus, D_A should be analyzed with some caution in young swimmers. That is, not always an increase in D_A can be related to a decrease in performance. As young swimmers go through growth and maturation processes, they increase their body features, more specifically their FSA (Morais et al., 2020a; Morais et al., 2021). Therefore, an increase in body features leads to an increase in swimming velocity as well as in D_A. Indeed, even in detraining periods this phenomenon occurs. It was noted that during an 11-week detraining period, swimmers increased their FSA (as well as other anthropometric features), and their swimming velocity and D_A (Morais et al., 2020a). This highlights the importance that anthropometrics have on swimming velocity and D_A. On the other hand, performing specific training to improve swimming technique may have a positive impact on the swimmers' D_A. For instance, Marinho et al. (2010a) aimed to assess the effects of 8-weeks of training in young swimmers' D_A. Although non-significant differences were found over time, the authors observed that later on, D_A and C_{DA} decreased in both genders. Authors argued that 8 weeks of specific swimming training were not sufficient to allow significant improvements on swimming technique (Marinho et al., 2010a). A reason for this non-significant effect can be the anthropometric factor, as young swimmers tend to increase their body dimensions. Furthermore, others aimed to understand the effect of D_A on swimming performance during an entire competitive season (Morais et al., 2014). It was noted that depending on the season moment and training periodization, the effect of D_A on swimming performance changes. At the beginning of the season, when the main aim is to increase energy, D_A is the main determinant of performance. Again, as D_A is strongly related to swimming velocity, an increase in swimming velocity will lead to an increase in D_A. This indicates that coaches of young swimmers should be aware that when the goal is to build energy quickly, this can lead to an increase in D_A and C_{DA} (variables related to swimming technique).

Sex effect

Studies have compared D_A between genders, whether among adults (Kolmogorov et al., 2021; Pendergast et al., 1977) or young swimmers (Barbosa et al., 2015a; Barbosa et al., 2013). In adults, D_A and the hydrodynamic coefficient at maximum speed in front crawl showed significant differences between genders (Kjendlie & Stallman, 2008; Marinho et al., 2010b; Xin-Feng et al., 2007). Based on the literature, it can be stated that front crawl is the most analyzed stroke and boys/men are more studied than girls/women. In any case, studies corroborate the idea that the values presented by men compared to women are always higher, in regard to strength and D_A (Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997). Initially, Toussaint et al. (1988b), who analyzed D_A in relation to speed in male and female swimmers, observed that differences in drag force and C_D are significant regardless of the speed in question. In addition these differences are also strongly present when all techniques other than front crawl are evaluated, ranging from 48.57 N to 105.88 N in men and 36.25 N to 77.01 N (Xin-Feng et al., 2007). In another recent study, in all swimming techniques regarding metabolic power, men showed higher values of metabolic power and greater mechanical efficiency than women (P_{ai} = 3346–3560 W and e_g = 0.062–0.068 vs P_{ai} = 2248–2575 W and e_g = 0.049–0.052, correspondingly in this order) (Kolmogorov et al., 2021). In all swimming techniques and for both sexes, values of metabolic power and mechanical power increased with exercise intensity (Kolmogorov et al., 2021; Pendergast et al., 1977). The opposite effect can be observed when technical components are analyzed, namely the influence of breathing on the effect of D_A during swimming. Formosa et al. (2014) demonstrated that male participants who exhibited a breathing action caused a greater net drag force (26%) compared to females (16%). This confirms once again that these authors agree with others who state that the increase in D_A is not synonymous with worse performance, but simply a natural increase in D_A when the performance is also better (Seifert et al., 2010).

In an approach aimed at young swimmers, in relation to all swimming techniques but mostly front crawl, studies show that several anthropometric, kinematic and efficiency variables were significantly higher in boys than in girls (Barbosa et al., 2013; Barbosa et al., 2015a; Morais et al., 2012). Comparing both sexes, Barbosa et al., 2015a indicated that most of the studied variables showed non-significant differences (controlled for sprint performance). Nonetheless, boys performed better than girls due to their larger constitution and natural physical development at these ages (Barbosa et al., 2015a; Barbosa et al., 2015b). Thus, it is evident that adults present much more solid results regarding the comparison between genders because young swimmers are in the process of maturation and growth. These changes in the morphology of young swimmers can constantly affect their hydrodynamics (Morais et al., 2015; Morais et al., 2020a). Likewise, Barbosa et al., (2015b) when analyzing the changes in the hydrodynamic profile of young swimmers throughout a season, realized that no variable had a significant sex effect, due to the fact that throughout the season the hydrodynamic changes occurred in a non-existent linear way. This is clear when analyzing the differences between the beginning and the end of the epoch, as the drag decreased when comparing these moments (-4.37±39.36%). Additionally, the study by Morais et al., (2014) corroborates this statement, confirming that the latent growth curve shows high variability in performance growth and that there is a significant effect on performance growth between genders.

Determinants of D_A

As shown in equation (2), D_A is dependent of speed, FSA, and C_D (in water density, which is constant). Initially di Prampero et al. (1974), pioneered the study of body drag and mechanical efficiency during swimming at speeds of 0.55 and 0.9 m/s. It was shown that the basic approach and the quantitative analysis of swimming proficiency were promising for the study of different forms of locomotion on and under the water surface. The studies by Zamparo et al. (1996) and Clarys (1999) found out that drag in the prone position under the water surface was greater than on the water surface, but the D_A reached twice the values of drag in relation to passive drag during swimming. The actual strategy implemented by swimmers to neutralize underwater torque tolerates a large increase in D_A (Zamparo et al., 1996; Zamparo et al, 2009). Lyttle et al., (1999) and Lyttle et al., (2000) aimed to analyze the variability and amount of drag at different speeds and depths. They showed that for speeds between 1.6 and 3.1 m/s there were no significant differences in drag forces recorded between the speeds indicated in front crawl, although the coefficient of the measures of variation for these tests indicated high reliability. However, although the differences are not significant, there is a tendency for the drag force to present a difference between the speeds, and it is evident that this force constantly increases (Lyttle et al., 1999; Lyttle et al., 2000). This may be because the applications of the towing device for swimming trawl research are widespread (Lyttle et al., 1999). It is necessary to take specific variables such as establishing the improved speed to start the underwater movement (Lyttle et al., 2000), in which results show that experienced swimmers should glide after pushing the wall until they decelerate to speeds between 2.2 and 1.9 m/s for maximum D_A reduction benefits at higher glide speeds.

When comparing the drag/velocity relationship, it was shown that greater drag forces promoted a greater intracycle variation of horizontal velocity (Lyttle et al., 1999; di Prampero et al., 1974). However, as drag depends on the square of velocity, a comparison between swimmers is only relevant when: (i) it is done at the same absolute velocity, or (ii) the effect of velocity is somehow controlled later (Barbosa et al., 2014). The same authors revealed that there were positive and moderate to strong associations between D_A and velocity (intracycle variation) when controlling for the effect of swimming velocity alone in each test (i.e., slip decay velocity method and perturbation velocity method) and swimming speeds in young swimmers as well. Thus, empirical research confirms the theoretical relationship defined for the intracycle variation of horizontal velocity and drag. It can be mentioned that this topic was first argued in the study by di Prampero et al. (1974). The authors reinforced the idea that a change in velocity affects mechanical efficiency because a change in velocity leads to a change in the body's reaction to water and similar variations in the mechanical efficiency and strength of the body. Another study indicated one relevant technique to estimate D_A (Shimonagata et al.,1999). The aim was to clearly show the relationship between swimming speed and D_A in front crawl swimming. This study was innovative at the time because the subjects were towed with the D_A system (a towing device like the ATM and VPM) in a hydrodynamic position and the subjects swam several attempts at maximum speed (with additional resistance and with towing by the D_A system) (Shimonagata et al., 1999). The propulsion, D_A, and swimming speed present a significant correlation, showing that swimming performance depends both on propulsion and D_A. Thus, it was essential to verify the existence of a balance between the power generated by the thrust forces and the power needed to overcome the drag forces in front crawl, evaluating the thrust and estimating D_A at maximum speed (Gatta et al., 2016). The authors noted that the swimmer's buoyancy force is very close to the force needed to reduce D_A (Gatta et al., 2016; Gatta et al., 2018). Furthermore, another study by Gatta et al. (2018) explored the relationships between mechanical power, thrust power, propulsion efficiency and sprint performance in elite swimmers, reporting that maximum speed in sprint swimming depends on the interaction between power in dry conditions (using a full-body swimming ergometer) and propulsion efficiency. Furthermore, the relationship between maximum velocity and power data was observed with the first method used (in the pool by measuring full tethered swimming force and maximum swimming velocity). The propulsion efficiency is about 40% and the drag is about 1.5 times greater than the values generally reported during passive drag measurements (Gatta et al., 2018). Furthermore, studies such as the one by Shimonagata et al. (1999) showed that swimming speed progresses with increasing propulsion and decreasing D_A (Gatta et al., 2016; Gatta et al., 2018; Seifert et al., 2010).

Frontal surface area is another major determinant of D_A. Knowing that FSA can dynamically change (i.e., variation) during the swimming stroke, researchers set out to assess whether a single FSA measure is adequate to obtain estimates of D_A and mechanical power (Morais et al., 2020b; González-Ravé et al., 2022). The authors noted that, in addition to FSA, swimming speed also changes during arm pull in front crawl, in young swimmers of both sexes (Morais et al., 2020b). There was a significant effect on the variation of the two variables of mechanical power and total input power, as well as on the measure of D_A (Morais et al., 2020b). Thus, it is worth mentioning that the variation of the FSA throughout the course cycle must be considered in the assessment of D_A (Morais et al., 2020b; Gatta et al., 2015; González-Ravé et al., 2022). Furthermore, Kolmogorov et al. (2021) recently determined that the FSA as a component of D_A force is the main reason for the differences in maximum speed among the swimming techniques, as there were no relevant differences for the mechanical and propulsion efficiencies. The body position and swimming coordination parameters have an important influence on performance in different swimming strokes (Zamparo et al 2009; Stosic et al., 2021). In addition, the body position and coordination between the limbs of competitive swimmers during the transition from underwater to surface swimming represented important factors in swimming speed, explaining 15 to 30% of the variation during the first stroke cycle (Stosic et al., 2021). This reinforces the idea that swimmers must carefully control the inclination and depth of the body and its coordination between the limbs, especially in the first stroke cycle after swimming underwater. Another study showed that waist indentation and buttock curvature can result in greater drag force and influence swimming performance. When differences in C_D exist, it may be due to the assumption used in D_A methodologies that a swimmer's velocity remains constant throughout the stroke cycle, rather than fluctuating, particularly in front crawl (Papic et al., 2020). D_A and C_D had a negative effect on performance, being related to the increase in speed during the act of swimming (Morais et al., 2021). There are also significant correlations between anthropometric variables and D_A (Barbosa et al., 2019). In addition, this also happens in front crawl, which results in 69% of the performance in young swimmers, for kinematic variables (efficiency), power in the water and strength on dry land (Morais et al., 2016). After a 10-week break, young swimmers show biomechanical improvements that are mainly explained by their normal growth. SF, $D_{A,}$ and C_{DA} remained unchanged, however, improving performance while maintaining D_A is a success factor (Moreira et al., 2014). An earlier study by Sharp and Costil (1989) found that the removal of body hair when swimming in breaststroke reduces the D_A, and, thus, the physiology cost of swimming. which directly influences the biomechanical performance of swimming.

Checking the external determinants that directly influence the performance and D_A of swimmers, Benjanuvatra et al., (2002) concluded that D_A values are lower in swimmers who wear competitive suits (Fastskin ™) when compared to traditional swimwear ($p<0.01$), not adopting a specific swimming technique, but a prone position. This variation occurred between 4.8% and 10.2%, and when the underwater flutter kick condition was excluded, all these differences were significant ($p<0.05$). Moriyama et al., (2021) showed that Jammer-type race swimsuits improve sprint performance to accompany the increase in maximum swimming speed compared to the conventional training swimsuit, in front crawl. In a relatively recent and innovative study, researchers showed that the AquaTrainer® snorkel does not lead to an increase in D_A during the front crawl performed over a wide range of speeds (Ribeiro et al., 2016). In addition, other studies have highlighted the importance of analyzing D_A as an important variable to be considered in training (Table 3), since the most advantageous pulling distance between members of the same team is between 0 and 50 cm from the lead swimmer, where drag is reduced by 21% and 20%, and in which 6% and 7% represent 50 and 100 cm from the lead swimmer. This is true for front crawl, in which maximal and submaximal speeds were analyzed (Barbosa et al., 2013; Kjendlie et al., 2004; Kjendlie & Stallman, 2008).

Drafting is certainly an underdeveloped subject in the literature, but it is known that the effect of distance between swimmers directly influences metabolic and hydrodynamic responses (Chatard & Wilson, 2003). A 4% body difference in underwater volume ($p<0.001$) between the two techniques in the 3D motion analysis also confirmed that the pressure drag and the friction drag were higher between the techniques (Gonjo et al., 2020). In a pioneering study by Yuan et al., (2019), it was shown that the hydrodynamic interaction between human swimmers can best be described and explained in terms of the interference effect of the wave on the surface of free water.

Overview and practical applications

It is important to mention that all experimental methods that exist to measure and evaluate D_A indicate that there is no agreement among each other regarding the values presented (Formosa et al., 2012; Toussaint et al., 2004). Nonetheless, all authors stated that all equipment measure the same phenomenon, and it can be said that none is more effective than the other (i.e., no gold-standard exists). They simply measure the effects differently and give different results. Some of the methods used were not completely reliable, as there is some margin of error; however, they highlight some issues that coaches should keep in mind not to apply in training or even to apply in an improved way, putting into practice some of the positive points applied in these studies, even if they present some margin of error. For example, the error in the Kolmogorov method can be attributed to the theoretical basis of the equal power assumption (Strojnik Bednarik & Strumbelj, 1999; Toussaint et al., 1988a; Toussaint et al., 1988b). Another analysis corroborated this by showing that the methods used measured essentially the same phenomenon of D_A (Formosa et al., 2012; Toussaint et al., 1988a; Toussaint et al., 1988b; Toussaint et al., 2004). It is probably more appropriate to state that these methods coincidentally underestimate the D_A coefficient by a similar magnitude.

D_A is defined by the change in characteristics resulting from the flow around different parts of the body following the movement performed. That is why it is essential to have a strategic notion of body movements throughout the stroke cycles, performing in continuous, active and less passive movements. This confirms the need of D_A to be further studied and transmitted to coaches. It is also necessary to understand the implications of D_A on performance in a homogeneous way. However, it is believed that decomposing total drag into pressure drag, friction drag and wave drag is useful to understand the physical mechanisms that determine drag.

The study of drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming (Pendergast et al., 1977). Thus, through the D_A research, it was possible to perceive that most studies present very important aspects of swimming technique, more practical movements and easy-to-maneuver variables, such as the distance between swimmers in a training session (aspiration cone), which can be changed depending on the group and type of work considered (Barbosa et al., 2013; Kjendlie et al., 2004; Kjendlie & Stallman, 2008). Furthermore, it will be essential to understand the drag variables regarding each of the four swimming techniques (Kjendlie & Stallman, 2008; Marinho et al., 2010b; Xin-Feng et al., 2007), observing that the values of drag and drag coefficient change completely (highlighting their oscillation and main difference).

Morais et al., (2011) showed that swimming performance in young swimmers is influenced by their swimming efficiency. Therefore, coaches and practitioners of young swimmers should design training programs with a focus on improving technical training (i.e., improving swimming efficiency), indicating that there are data showing that swimming performance is dependent on the SI (an efficiency estimator) and this, in turn, on *dv*, SL, AS, and D_A (Morais et al., 2011). Considering the performance, latent modeling (modeling a latent growth curve) is a comprehensive way of collecting information about the performance of young swimmers over time. The performance improvement was influenced by the different variables, as well as showing an intra and inter subject variability between genders (Morais et al., 2014; Morais et al., 2015). Otherwise, cluster stability is a feasible, comprehensive and informative method of obtaining information about changes in young swimmers over time. Swimmers can be classified into different clusters based on their performance and determinant factors (Morais et al., 2015).

Finally, it can be confirmed that the resistive or drag images found during swimming greatly influence the swimming performance of swimmers of different age groups, including those in elite competition. The benefits of understanding the factors that affect drag are found to improve performance in this sport in different ways that can be analyzed (Sacilotto et al., 2014). However, current techniques used to measure or experimentally estimate drag values are questioned as to their consistency, thus limiting investigations to certain factors. A recent problem is to understand the best method to be applied to study and analyze the variables considered and to determine a context and purpose. Knowing that the range of methodology is wide but not specific, it can bring some confusion to the process, despite being multifaceted (Sacilotto et al., 2014).

Conclusions

Regarding numerical studies, considering all swimming strokes for a constant submaximal and maximum speed, it was found that the variation in buoyancy torque is much greater during breaststroke and butterfly than during front crawl and backstroke. Experimental studies observed that D_A is greater in adults than in children. It is also meaningfully different between sexes with greater values achieved by males. Furthermore, it is evident that speed and FSA are the biggest contributors to the increase in D_A (adults have a higher D_A value because males and adults tend to have higher speed and FSA). Finally, the technical training dedicated for this purpose makes it possible to reduce D_A and C_{DA} and thus improving performance. Through longitudinal studies with pre and post-test it is possible to understand the variability of drag throughout the season and to understand the progression and changes in performance. The intensity of the drag force depends on some factors, among which it is possible to highlight the swimming technique and the morphological characteristics of the subject. The FSA appears as the main morphological characteristic of the subject, having a preponderant role in the determination of the drag force intensity.

It is necessary to understand how the resistive forces in swimming are measured and calculated, because like any method they demonstrate strengths and weaknesses in the evaluation of the techniques described in swimming. Furthermore, it can be indicated that D_A is higher in men than in women, while C_{DA} is not clear in the literature as to its significance between genders. Nevertheless, it is known that the C_{DA} between the sexes cannot behave in a different way, because swimming efficiency depends on the drag coefficient. In this sense, the drag coefficient will also show a significant result. Notwithstanding, it should be mentioned that these results and outputs are based on discrete variables measured during an entire trial. Future studies should be conducted to understand how D_A and C_{DA} can change within a stroke cycle in all four swimming strokes.

Techniques used to measure drag in swimming through experimental and numerical methods

One method for determining drag is Kolmogorov's Velocity Perturbation Method (VPM) (Kolmogorov & Duplishcheva, 1992). This is based on the principle of conserving the swimmer's maximum propulsive mechanical power in two distinct swimming situations, both at maximum speed: Free swimming and swimming towing an additional drag device. The hydrodynamic drag in both situations is compared and corresponds to the active drag (D_A) in the situation, that is, it is added to the known free swimming drag of each swimmer, making the hydrodynamic effect of the body known. Having a huge advantage in obtaining data that discriminates the degree of drag that the swimmer performs for a given swimming distance, especially in high competition and even greater importance for distances in which the swimming speed will be maximum. It should also be noted that it is a methodology applied in real practice and that allows us to carry out tests on swimmers on how to swim for 4 swimming techniques (something still lacking in the literature in an effective way).

It should also be noted that the necessary added drag (caused by the hydrodynamic body) has never been measured and/or disclosed in a discriminatory way by the scientific community. There is only one equation to estimate the additional drag from the added drag, and then calculate the swimmer's drag. One way to check this drag specifically is through CFD (Computational Fluid Dynamics) (Kolmogorov & Duplishcheva, 1992).

Computational Fluid Dynamics (CFD) consists of carrying out numerical simulations, through iterative calculations that solve predefined equations, which allow obtaining the desired results. The mathematical model is applied to the fluid flow. The forces generated by a swimmer's hand/forearm, resistance (Fd) and lift, are a function of fluid velocity. Since the hand/forearm model is fixed and taking into account the area of the model's projection in the plane perpendicular to the force for different angles of attack (θ=0º, 90º, 180º) - (A1=0.0107m2, A2 =0.0191m2, A3=0.0103m2) - and the density of the fluid (ρ). The simulations carried out (Silva et al., 2005; Marinho et al., 2010) made it possible to confirm the importance of using CFD in pure sports Swimming, as well as confirming, through comparative analysis, the values of the computational coefficients obtained.

Regarding propulsive force, tethered swimming is a method used to determine the power generated by the swimmer during a swim (Vorontsov, 2011; Morouco et al., 2014). A strong relationship between tethered strength and swimmer speed has indeed been reported by several authors (Vorontsov, 2011; Keskinen, Tilli & Komi, 1989). Estimating the drag force (Fd) through experimental cases of passive towing necessarily leads to an underestimation of the power required to overcome the drag forces, since passive drag is smaller than drag (Gatta, Cortesi, Fantozzi, & Zamparo, 2015). Thus, several studies have attempted to measure swimmer Fd in active conditions (di Prampero, Pendergast, Wilson, & Rennie; Holmer, 1974; Kolmogorov & Duplischeva, 1992; Clarys, 1979; Zamparo, Gatta, Pendergast, & Capelli, 2009).

Furthermore, in recent years there have been several attempts to estimate Fd by applying CFD simulation to the flow of a swimmer (Bixler, Pease, & Fairhurst, 2007; Zamparo, Capelli, & Pendergast, 2011). Still, the scientific discussion about the best method to evaluate drag continues to be a controversial issue within the scientific community (Bixler, Pease, & Fairhurst, 2007; Zamparo, Capelli, & Pendergast, 2011). Although the swimmer's movements during active propulsion create additional drag (Toussaint, Roos & Kolmogorov, 2004), trying to understand whether propulsive drag is proportional to D_A is not evidence that is well studied in the literature. That is, we try to understand whether the force that the swimmer exerts to promote displacement is proportional to the force of the water that is exerted on the swimmer. To do this, it is necessary to study D_A and the force exerted during swimming (propulsive drag) through other methods of assessing propulsive force, which do so directly. Furthermore, it will be important to verify this phenomenon for the four swimming techniques, as the literature only reports data for the crawl technique (Barbosa et al., 2013; Gatta, Cortesi, Fantozzi, & Zamparo, 2015; Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997; Xin-Feng, Lian-Ze, Wei-Xing, De-Jian, & Xiong, 2007).

The authors (Gatta at al., 2015) state that crawl and butterfly techniques are the swimming movements with the best "drag efficiency". In this way, it was possible to investigate the hypothetical relationship between drag and propulsive drag, making it possible to estimate the drag efficiency: for a speed of 1.5 m s –1, it varies from 0.035 to 0.038 (swimming prone and back, respectively) to 0.052 –0.058 (moth and crawl, respectively). Thus, the aim is to study sequentially the effect of drag on competitive swimming and verify the veracity of the drag estimation (hydrodynamics) described in the literature.

Drag assessment techniques in recent years

For many years attempts have been made to accurately measure D_A and passive drag (D_P) in swimming. However, there has been much controversy as different techniques have produced varying values of drag (Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Xin-Feng, et al., 2007). The energetic approach, numerical solutions, and experimental techniques have been developed and used to estimate or measure drag forces in swimming (Bixler, Pease, & Fairhurst, 2007; Bixler & Schloder, 1996; Lyttle, Blanksby, Elliot, & Lloyd, 1998; Marinho, Barbosa, et al., 2010). All techniques were modified and criticized as the need to truly understand what forces result from resistance in swimming increased.

The energy approach

The energetic approach investigates the theoretical relationship between the energy costs of swimming, speed, the swimmer's overall mechanical efficiency, and body drag. Mechanical power is deciphered through calculations from this same theoretical approach, deciphering the mechanical power produced by swimmers. In this technique, the swimmer is towed while swimming at a pre-defined pace (figure 1). The swimmer performs the swim with added weights designed to provide resistance to the swim (Zamparo, et al., 2009). Maximum oxygen consumption is also recorded throughout each attempt to understand the swimmer's energy expenditure at a given average speed. Swimmer body drag is determined by adding (or subtracting) extra loads from swimmers moving at a given speed (Clarys, 1979; di Prampero, et al., 1974; Zamparo, et al., 2009). The extra drag is measured and related to the swimmer's energy expenditure to calculate drag as well as the swimmer's mechanical efficiency. To calculate drag, a linear relationship was identified between drag and maximum oxygen consumption (VO2max) at constant swimming speeds, which led to this technique for determining drag being a function of VO2max. At constant average speed, the average propulsive force exerted by the swimmer will be equal or opposite to the D_A produced (di Prampero, et al., 1974).

Some of the researchers (di Prampero, et al., 1974; Holmér, 1974) who used the energetic approach when comparing propulsion efficiency values in percentages, noticed that there were similar values of drag. Although the intrastate drag values are similar, it should be noted that these authors assumed that propulsion efficiency did not change between tests where drag was calculated. Even at a constant speed, it is possible for propulsion to change when external loads are applied to the swimmer, as happens when approaching drag. Therefore, if D_A is affected by this change, swimmers' VO2max values will also be affected due to small deviations in propulsion efficiency (di Prampero et al., 1974). Furthermore, when introducing a snorkel to measure VO2max, the swimmers' superficial frontal area (FSA) is changed (there may be an exclusion of drag caused by this material). But it will be important to state that although this technique for estimating D_A produced a questionable result, it was the first to describe the drag of a front-stroke swimmer. However, even with these possible pioneering gaps, it was important to determine D_A values between male and female swimmers, swimmers with different swimming speeds, as well as the analysis of energy in swimming in liquid media (Clarys, 1979; di Prampero et al., 1974; Toussaint et al., 1988).

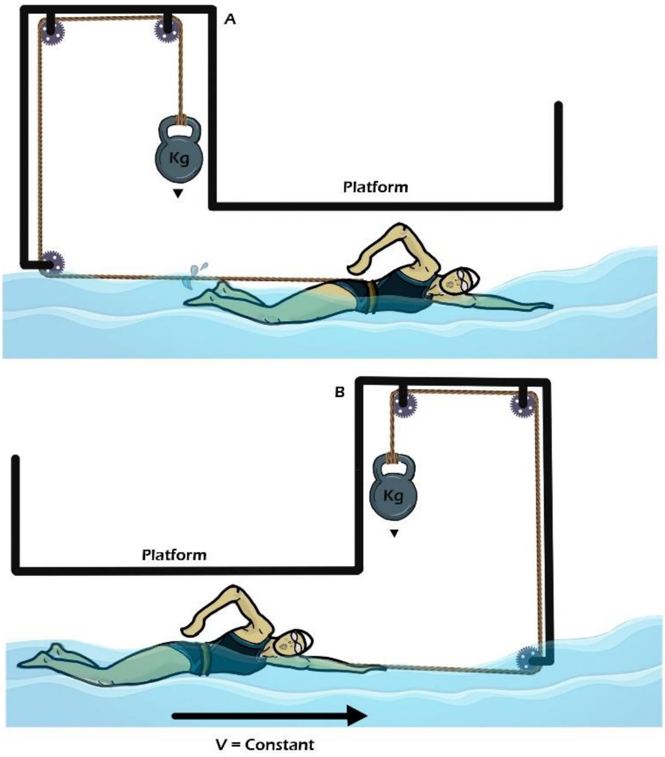

Figure 1. Experimental setup adapted from the trawl collection of di Prampero et al. (1974)

The numerical simulation

The resistive forces caused by the flow of water when it is in motion can be determined through numerical simulations (using computer modeling). Through CFD, the drag force can be measured (numerical solutions) solving and analyzing problems involving the flow of fluids through computer simulation, this being a more recent method that can be analyzed (Marinho et al., 2010). Using this method, the researcher can analyze models on a computer, for example, a 3D model of a swimmer. From this model you can simulate the desired movement patterns to provide feedback on the change, such as a modification in stroke technique in order to obtain the best performance when compared to the movement drag obtained (Bixler, Pease, & Fairhurst, 2007; Bixler & Schloder, 1996). Previous versions of this computational programming describe that manipulating a model through CFD in a human form will be a limiting factor due to the lack of freedom to manipulate the model's movements in swimming (Silva et al., 2005). This is due to the limited amount of mechanical changes during a course used in the protocols detailed in the different studies (Barbosa et al., 2010; Bartlett, 2014; Bixler et al., 2007; Bixler & Schloder, 1996; Marinho, Barbosa, et al., 2010; Marinho et al., 2010). Bixler & Schloder (1996) introduced two-dimensional CFD into the world of swimming and after a period of more than six years the first three-dimensional CFD study emerged. Since these landmark studies on swimming CFD, several authors have investigated hydrodynamic drag using this method (Marinho et al., 2010).

CFD simulations allow us to understand the variability caused by the model (swimmer). In this way, through CFD we can change this behavior in order to improve performance within the fluid.

This is exactly what Bixler et al. (2007) presented in their study, characterizing the water flow and the drag force caused by human displacement in its environment (considering a submerged and hydrodynamic position). For this purpose, a CFD model of a real swimmer in virtual form was used. Although this study only investigated the effects of D_P, the results were positive. Managing to achieve the much-desired objective of establishing a CFD model of a real submerged human body and the effects of D_P were effectively achieved. The use of this method in the evaluation of resistive force is very promising and the results of the previous article represent a necessary first step towards a more complicated CFD analysis in which D_A can be evaluated.

Regarding some less positive aspects about this evaluation method, it is the fact that this measure requires the collection of basic kinematic measurements caused during the swimmer's course, such as, for example, the swimmer's center of gravity and base position, speed instant swimming. An additional limitation of this method is the fact that CFD simulations require an enormous amount of computing time. Furthermore, correcting errors caused by the flow and abnormal movement of human swimming may be difficult to solve in computation. These problems can further increase the complexity and computational costs of the simulation, making it difficult for coaches and scientists to use this method in a simple, accessible and efficient way in their training routines.

Experimental Techniques

Various experimental techniques have also been carried out and developed to try to accurately determine the resistive forces encountered by a swimmer. The most frequently encountered techniques include direct measurement of D_A via the measuring D_A system (MAD system) (Hollander et al., 1986), indirect techniques of collecting drag values, for example, the velocity perturbation method (VPM) (Kolmogorov & Duplishcheva, 1992) and the assisted towing method (ATM) (Alcock & Mason, 2007; Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992).

To directly measure D_A, Hollander et al. (1986) developed the MAD system. This device measures the drag force generated by a swimmer, which allows the calculation of the propulsive force produced during the test. To obtain the propulsive force, it was assumed that the average propulsive force would be equal to the average active drag values when the swimming speed was constant (figure 2) (Hollander et al., 1986).

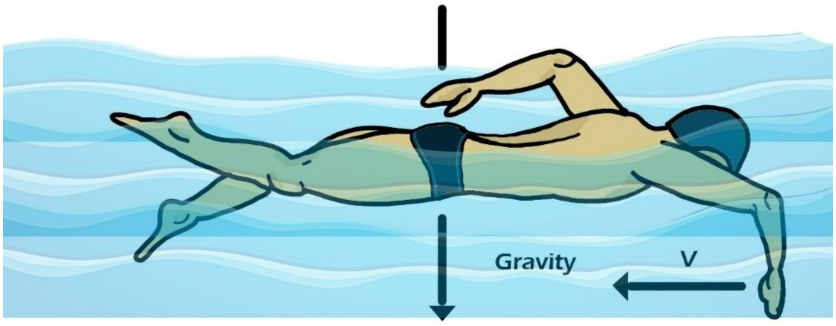

Figure 2. Schematic overview of the forces acting on the entire swimmer and the swimmer's hand. The driving force can be based on drag or lift. where the D_A is carried out in the direction of *V* (adapted from van Houwelingen et al., 2017).

The MAD system (figure 3) is performed with the swimmer swimming away from the cushions that are fixed underwater (Hollander et al., 1986). In the original study, ten tests were carried out at different but constant speeds. The swimmer's legs were restrained by using a small pull buoy (Hollander et al., 1986). Through the swimmer's height, the depth of the cushions is changed as well as the distance between them. To determine the average force, each trial of the signal recorded by the force transducer through telemetry is considered. The average propulsive force was calculated by integrating the force records at a constant swimming speed. In this investigation, each test produced ten data points of propulsive forces at ten different speeds, which ranged from minimum to maximum swimming speed (Hollander et al., 1986).

Hollander et al. (1986) found the function to calculate D_A, however, (Toussaint, Roos, & Kolmogorov, 2004) presented the drag calculation as:

$$D_A = Kv^2 \qquad (1)$$

where D_A represents active drag, K is a constant (incorporating density, drag coeficiente (C_D) and frontal surface area (FSA)) and v equals swimming speed.

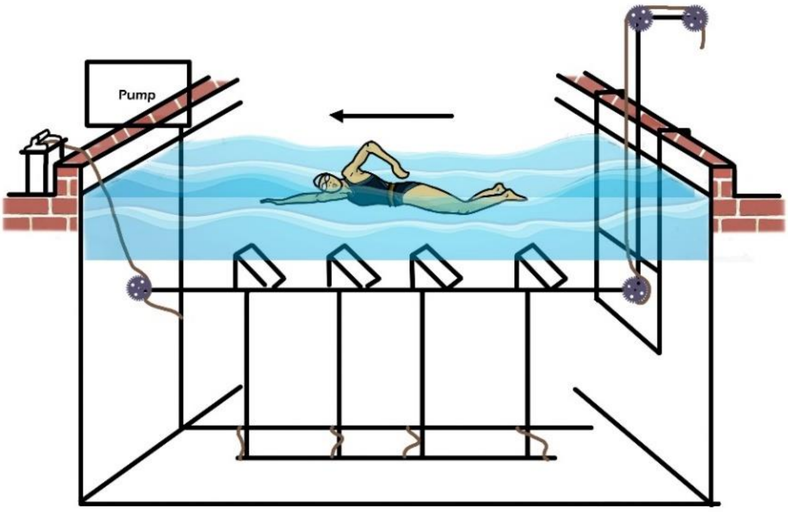

Figure 3. MAD system configuration for trawl collection, adapted from Hollander et al. (1986).

The MAD system has been widely used by researchers to determine fixed values of D_A produced in the aquatic environment during swimming (Alcock & Mason, 2007; Barbosa et al., 2013; Figueiredo, Willig, Alves, Vilas-Boas, & Fernandes, 2014; Gatta, Cortesi, Fantozzi, & Zamparo, 2015; Gatta, Cortesi, & Zamparo, 2016; Hazrati, Sinclair, Ferdinands, & Mason, 2016; Hazrati, Sinclair, Spratford, Ferdinands, & Mason, 2018; Hollander et al., 1986 ; Kolmogorov & Duplishcheva, 1992; Mason, Formosa, & Toussaint, 2010; Mason, Sacilotto, & Dingley, 2012; Narita, Nakashima, & Takagi, 2017, 2018; Toussaint et al., 1988; Xin-Feng, et al. , 2007). In any case, there are still many criticisms of the MAD system due to the differentiation of values obtained by this technique. The main reason for such constructive criticism by researchers will be the fact that this system limits the natural mechanics of a swimmer's stroke and can only be used at a constant speed. Therefore, the results of this technique should only be compared if the swimming speed is the same between techniques to criticize the same technique used. Another criticism is that the MAD system protocols only allow the swimmer's hands to come into contact with the pads and do not react with the water as the swimmer normally would. Hollander et al. (1986) observed that normal hand trajectories can be altered with this technique; however, it was justified by stating that, at the same swimming speed, a different trajectory of the hand does not necessarily imply a difference in D_A. Poizat et al. (2010) used this method as a training device for biomechanical assessment and performance analysis of swimmers. The swimmers involved in this study described that it was difficult to make contact with the pads, especially at high speeds. This technique is, however, well established and an effective way to directly measure the forces encountered and produced by a swimmer's upper body during a maximal effort (Poizat et al., 2010).

The VPM (Velocity Perturbation Method) approach is based on the assumption that a swimmer is capable of producing an equal amount of useful power and that the swimmer moves at a constant speed. This technique is seen as a progression of the energetic approach to drag estimation (Kolmogorov & Duplishcheva, 1992; Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997). However, this technique does not describe the maximum rate of oxygen consumption. In this method the swimmer must produce two equal maximum efforts. This technique is more reliable and convenient at distances of 25 m, however it can be used at other distances. In the first sprint, the swimmer swims "freely" - without any accessories - and the second sprint is swum with a hydrodynamic body connected to the swimmer (both at the same distance), creating a known and limited additional resistance. The maximum average speed when swimming with the hydrodynamic body was compared with the maximum average free swimming speed, which together with the known additional resistance, is used to calculate the free-swimming D_A:

$$D_A = \frac{D_b v_b v^2}{v^3 - v^3{}_b} \qquad (2)$$

where D_b is the additional resistance of the disturbance buoy and v_b and v are the swimming speeds with and without the hydrodynamic body, respectively (Kolmogorov & Duplishcheva, 1992).

Although it is a method much researched by the scientific community, VPM is criticized, as it is an indirect technique for measuring drag and, therefore, the values found may be overestimated (Marinho, Garrido, et al., 2010). Furthermore, the values achieved depend greatly on the competitive level of the participating swimmers, when referring to the conjectures to which this technique adheres (Toussaint et al., 1988). The first conjecture depends on the swimmer's skill level, the rest interval between tests and whether the swimmer understands the experimental conditions, so motor self-control is important (Bideault, Herault, & Seifert, 2013). This suggests that the use of this technique, and others that use the same power premise, should limit participants to those who consider themselves semi-elite or elite swimmers. The second conjecture of constant speed limits the study of fluctuations during the course, known as comfort/discomfort during swimming, normally produced in a frontal swimming path (Kolmogorov & Duplishcheva, 1992).

Kolmogorov and Duplishcheva (1992) revealed variable speed during trials, and these speed fluctuations during travel were approximated using a computer simulated Strouhal number. The maximum error due to stroke cycle fluctuations was found to be 6 to 8%. As the VPM is reliable using a constant speed throughout the resisted tests, fluctuations were decreased to maintain an almost constant speed. Furthermore, the hydrodynamic body used was constructed so as not to decrease the swimmer's speed by more than 10% (Kolmogorov & Duplishcheva, 1992).

As a result of the near-constant speed conjecture, a series of physical hydrodynamic positions, each with a different additional resistance, were developed to eliminate dependence on the swimmers' performance level. However, it has been observed that the additional resistance created by a hydrodynamic body can be affected by the buoyant movements generated by the hydrodynamic position (Xin-Feng et al., 2007). To overcome these shortcomings, Xin-Feng et al. (2007) proposed the development of a simple and convenient device to estimate drag at maximum speed based on the equal power assumption and the VPM approach. Figure 5 illustrates the device developed by Xin-Feng et al. (2007), which maintain the additional resistance in a stable position. This system minimizes the swimmer's buoyant movement in the hydrodynamic position and allows changes in the amount of resistance acquired during a swim stroke.

The force transducer (shown in figure 4) was used to measure the variation in tension in the "thread" of the device, when the sliding object (on the cable) was moved by the swimmer during the test route. The results revealed that cable tension is variable, as Kolmogorov and Duplishcheva (1992) had later assumed. Therefore, in the original VPM approach, even if the speeds were defined as constant, the D_A values could differ due to the speed fluctuation restrictions and also the resistance acquired by the device used.

Despite its limitations, VPM has several strengths. For example, this technique can be configured in any swimming pool (being a portable device). This means that testing can occur in internship phases or during preparation for a race, which can provide important coaches and athletes with information and details at a point in time that is considered useful. On the other hand, the MAD system cannot be used in such a simple way, as it requires a long configuration time. Also compared to the MAD system, the VPM requires little or no adaptation to obtain an analysis in other swimming styles (e.g. butterfly, backstroke or breaststroke). A comparison between the systems made by Toussaint et al, (2004) revealed that the two techniques produced significantly different drag values. Given the limitations of resistance, of the "unnatural swimming movement" that both techniques have, this significant difference does not imply that the technique is wrong or that it measures different aspects of swimming.

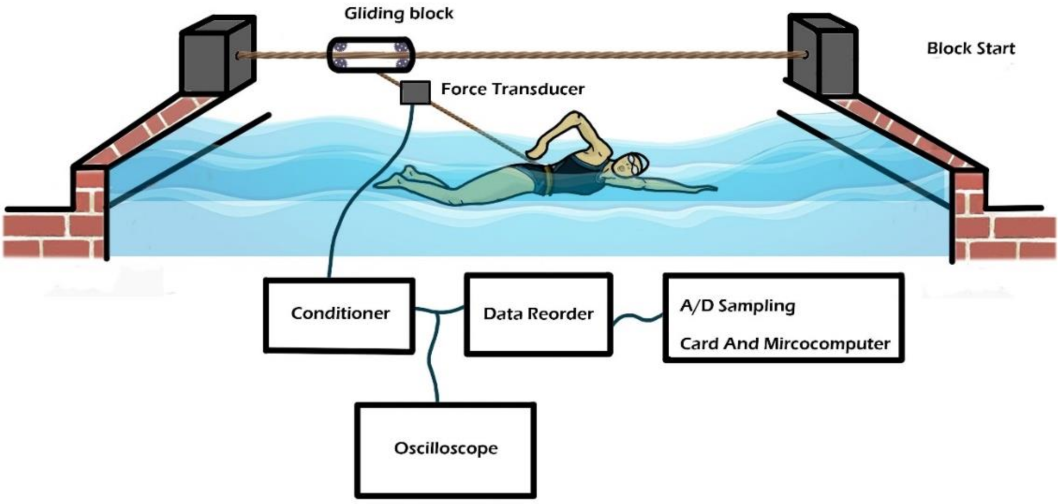

Figure 4. Modification of the VPM approach as used and adapted from Xin-Feng et al. (2007)

The ATM technique (Assisted Drag Method) is a more recent technique that also allows the D_A to be estimated. Few studies (Alcock & Mason, 2007; Formosa, Mason, & Burkett, 2011; Mason et al., 2010; Mason et al., 2012; Mason, Thibault, & Misener, 2006; Sacilotto, Ball, & Mason, 2014) have been published using this technique to determine drag. In this method, the swimmer is assisted during swimming and not resisted, unlike the VPM method, as shown in figure 5. The ATM is also based on the conjecture of equal power and constant speed pressures. However, as described by Xin-Feng et al. (2007) and recognized in Kolmogorov and Duplishcheva (1992), a swimmer will not be swimming at a constant speed at any time during a maximal effort due to inter-stroke fluctuations in front stroke swimming. Such fluctuations are the result of forces carried out during the swimming stroke that are generated during a natural stroke and kick cycle.

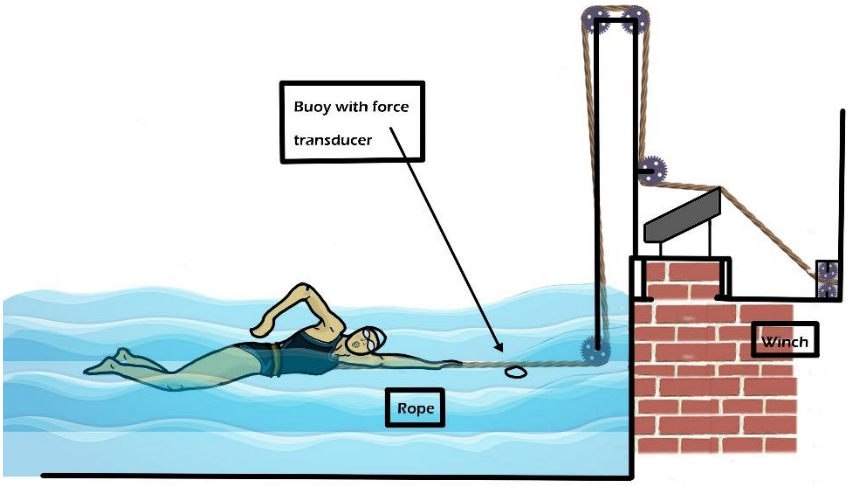

Figure 5. Schematic drawing of the electronic box mounted on a starting block (Sacilotto, Ball, & Mason, 2014).

To better understand these fluctuations (used in VPM), Mason et al. (2012) compared constant D_A values with fluctuating D_A values (figure 4). During testing, the differences between the free swim and without any accessories at maximum speed and the towed swim speed (towed using the dynamometer) are used to calculate the drag in relation to the drag force required to tow the swimmer. The same calculations as the VPM approach are used, however the final equation for estimating drag using ATM is changed to:

$$D_a = \frac{F_b v_2 {v_1}^2}{v^3{}_2 - v^3{}_1} \qquad (3)$$

where F_b is the force required to tow the swimmer during the acceleration of speed along the swim route, measured on the force platform, $v2$ is the speed with resistance through towing and $v1$ is the maximum free-swimming speed. In order for the tow to allow for fluctuations during the swimmer's stroke, the force setting on the dynamometer is reduced and the speed setting is increased to 120% of maximum freestyle speed. The towing dynamometer must also be adjusted so that, when the force configuration is reached, it fluctuates at the towing speed, making it possible to maintain this obtained force configuration (allowing fluctuations during the swimmer's journey).

The towing dynamometer must also be adjusted so that, when the force configuration is reached, it fluctuates at the towing speed, making it possible to maintain this obtained force configuration (allowing fluctuations during the swimmer's journey). The force setting used is a predetermined fraction of the swimmer's D_P tow (hydrodynamic tow at maximum free-swimming speed) and is different for each swimmer. Despite the increase in speed, defining the average speed caused by the tow will still be between 5% and 10% greater than the maximum average speed of freestyle swimming. However, when the speed profile is calculated, it will demonstrate the fluctuations made throughout the route. The use of the ATM approach, by allowing a floating trailer speed in the D_A estimation, is still at a very early stage, requiring a more recent and futuristic approach for improvement. However, the results shown so far are positive, in terms of deciphering exactly what affects performance during free swimming, which is the main objective of all those seeking to better develop this modality. Sanders et al. (2012) conducted a recent review and noted that the work presented in Mason et al. (2010) really needed validation although it turned out to be a promising project. Since then, several new articles have been published using the ATM technique (Sacilotto et al., 2014).

When towing at a constant speed, it was assumed that the drag was equal to but opposite the direction of propulsion. Another study that used ATM developed calculations to obtain the propulsive profile, net force and acceleration curves of a swimmer, allowing fluctuations to occur during the course. Mason et al. (2012) present D_A as a negative value, with the propulsion equation (P) as:

$$P = \frac{d}{dt}(mv) - D_a \qquad (4)$$

where m is the swimmer's D_P force (as a proxy for a swimmer's mass), v is the velocity profile, and D_A is the active drag profile presented as a negative value (P is the propulsion profile presented as a positive). Practical applications using ATM and this propulsion equation also look promising. However, the validation of this method is still in question, as there is no key experimental standard to validate it. In an attempt to somewhat validate this technique, a readability study (Sacilotto et al., 2014) was carried out using ATM, however, with a constant speed trailer. However, there is a large gap, it only includes a small sample number, and thus the results revealed a very good reliability value for the mean D_A values within the subject (interclass correlation of 0.91, with a confidence limit of 95% and a probable range of 0.58 and 0.98) (Mason et al., 2012; Sacilotto et al., 2014).

More studies on this topic are still needed to determine the viability of this ATM method. It is also necessary to re-evaluate investigations into the speed/force profiles obtained with this technique to determine whether they truly mimic the mechanics of the swimmer's real stroke. Furthermore, similar to the MAD system, the ATM technique has only presented work on the investigation of resistive and propulsive forces of frontal swimming. It can be assumed that research for other swimming styles, using ATM, can be carried out following the same protocols as the front swimming (more precisely, the back swimming). However, investigations into butterfly and breaststroke swimming seem to be forgotten, given the large fluctuations and variations in speeds performed during swimming. A very important step would be to obtain useful and real drag for all swimming techniques, considering semi-elite and elite swimming.

Drag assessment techniques in recent years, changes and perspectives

Recent studies by Narita et al. (2018) compared D_A with and without leg kicks, each swimmer performed the front swim using arms and legs and using only arms. To restrict the movement of each swimmer's legs during the test, swimmers were instructed to place a buoy between their thighs and strap their ankles. However, when measuring the resistance force in the hydrodynamic position, which is a prone position with arms raised, the buoy and band were not used. In all experimental phases, the swimmer wore a snorkel to eliminate the influence of his breathing movement. Furthermore, swimmers wore the same type of competition suit to eliminate the influence of suit differences on endurance strength (Gatta et al., 2015; Mollendorf, Albert Termin, Oppenheim, & Pendergast, 2004). This method is a more advanced phase of the energy approach used previously described. The method used is known as MRT (residual thrust measured values) developed by (Narita et al., 2017). Before measuring the value of the residual impulse, which is the difference between the propulsive force and the resistance force, to evaluate the D_A in swimming speed, each swimmer voluntarily pushes. Given that this study evaluated the effects of drag, other potential factors may require future consideration (e.g., trunk tilt and swimming technique). Furthermore, it is necessary to consider the characteristics of each swimmer in relation to the contribution of the stroke (Formosa, Toussaint, Mason, & Burkett, 2012). However, no specific characteristics were observed in terms of frequency and duration of the stroke cycle in the swimmer used. Therefore, in the future, it would be useful to evaluate resistance forces in swimming using the MRT method combined with three-dimensional motion analysis (Blocken, Defraeye, Koninckx, Carmeliet, & Hespel, 2013; Vilas-Boas et al., 2015), considered of CFD.

The study by Hazrati et al. (2018) reported that the drag force in swimming can be calculated from a function of five different variables: swimming speed, towing speed, “belt” strength, power and speed exponent. The accuracy of the drag force value depends on the accuracy of each variable and the contribution of each variable to the drag estimate. To calculate the uncertainty in the drag value, the derivatives of the D_A equation were obtained in relation to each variable. They were then multiplied by the uncertainty of that variable taking into account the VPM and MAD model. The result of the uncertainty of the velocity exponent indicated a contribution of about 6% error in the D_A. The contribution of unequal energy production showed that if an energy changed by 7.5% between conditions, it would lead to about 30% error in the calculated drag. Consequently, if a swimmer did not maintain constant power between conditions, there would be substantial errors in the drag calculation. Therefore, we can state that the results of this study show that there are some errors in measuring D_A using the ATM. The measured variables (swimming speed, towing speed and strap strength) presented the least uncertainty. The contributions of these uncertainties to drag values were approximately 6 to 7% error in free swimming and towing speeds and 2 to 3% in belt force, whereas if power changed by 7.5% between conditions, this would lead to about 30% error in the calculated drag. This problem can be solved if a swimmer produces the same power in free swimming and tow-assisted swimming conditions. Therefore, confirming the need to reevaluate the methods used for better data accuracy on the topic of D_A.

Seifert et al. (2015), like other authors, also examined the relationships between the coordination index and drag, assuming that, at constant average speeds, average drag is equal to average propulsion. The relationship between the coordination index and propulsive efficiency was also investigated at maximum speed. This study used the MAD system, where swimmers were instructed to swim at a constant speed, focusing on a constant stroke rate.

However, these recent studies continue to use many of the older methods, but with access to more up-to-date tools. We inform that these methods are important, but it will be necessary to improve the methods used to determine D_A in swimming. Futuristic and innovative studies are necessary and important.

Future studies may be related to CFD, as used by Sadeghizadeh, Saranjam, and Kamali (2017), who carried out a study on the drag force exerted on the swimmer's body. The main objective of this research was to evaluate the swimmer's power to/when achieving high-speed movement in the water. The author described that in the last decade, the swimmer's movements at low speeds were studied by researchers for sporting purposes and improving time recording in competition, while in this research the authors tried to increase the swimmer's speed by up to 8 m/s using the electric drive system. The numerical simulations were carried out using CFD considering three-dimensional turbulent flow based on the Volume of Fluid (VOF) method. The geometry of the swimmers' bodies was generated by three-dimensional modeling and modeling images of real swimmers. Concluding that any swimmer who swims at greater depths and with greater D_A (up to a certain value), the drag force exerted on him will be reduced. Being an added value to understand that in underwater swimming the hydrodynamic values are higher, however, in high competition it is important to understand what the ideal values are to reduce the D_A during the execution of the swim during the course in all swimming techniques.

Key Points

Swimming performance largely depends on the phase in which the test is performed. Being a modality with a long training process, it would be important to take into account the optimal phase for carrying out the test. Therefore, gains or losses in this aspect of a swimming performance can significantly affect the test result. The aim of this article is to evaluate and describe current techniques used to estimate drag in elite swimming. We also highlight the futuristic perspective of evolution on the methods to be used so that they can be more influential depending on the stage in which the swimmers are without affecting the results obtained.

The techniques obtained for the experimental use of drag found in the literature seem to be based on the ideals of the energetic approach in relation to the production of mechanical power, although these were established in the 1970s. Stating then that even with some more modern methods and possibly more valid for the scientific community, more recently, indirect experimental techniques, although limited, have been found more frequently in the literature. The MAD system, which is the only system to directly measure D_A, has been shown to have a large number of limitations with regards to maintaining the natural mechanics of the swimmer's movement. Although, when compared to ATM and VPM, the MAD system is more established and can be compared with itself. Alternatively, VPM is a more economical technique and can be transported easily, unlike the MAD and ATM systems, where installation time and equipment cost are quite high. Researchers prefer to use an indirect assessment because it allows swimmers to perform natural stroke mechanics while swimming. This being the main objective of this topic (to make a reliable and natural drag value for a given swimmer and a given swimming technique), allowing a normal speed fluctuation, which can be achieved using the ATM method. The only concern among the scientific community when referring to indirect methods will be the fact that the assumptions associated with the testing protocols are not completely secure. To overcome these assumptions, the CFD method seems to be the best option to determine resistive and propulsive forces in swimming. However, until basic kinematic measurements can be determined in swimming, CFD research also relies on experimental assumptions. Still, we can consider this method as a pioneer in determining the drag and propulsion of swimmers in all swimming techniques.

Although this framework is not exhaustive of all techniques used worldwide in measuring or estimating drag, it is possible to obtain a clear outline of the most commonly used techniques. Therefore, as a guide, the choice of technique or method used to estimate, or measure drag should depend on what researchers want to achieve from the test. For the quest to understand what D_A really is, the assessment technique that allows a swimmer to be the most natural in the water, or be able to be simulated naturally, may be the best scientific step forward. Therefore, considering all the protocol methodology described here, we can assess that the best possibility in the coming years could be the CFD technique that more easily encompasses all the hydrodynamic capacity of towing and free movement that swimming allows and intends to do so.

Chapter 3. Experimental studies: evaluation tools, standards and operating tests/protocols

Study 2. Using Wearables to Monitor Swimmers' Propulsive Force to Get Real-Time Feedback and Understand Its Relationship to Swimming Velocity

Abstract

Evidence on the role of propulsion compared to drag in swimming, based on experimental settings, is still lacking. However, higher levels of propulsion seem to lead to faster swimming velocities. The aim of this study was to understand the variation in a set of kinematic and kinetic variables between two swimming sections and their relationship to swimming velocity. The sample consisted of 15 young adult recreational swimmers (8 males: 20.84 ± 2.03 years; 7 females: 20.13 ± 1.90 years). Maximum swimming velocity and a set of kinematic and kinetic variables were measured during two consecutive sections of the swimming pool. Differences between sections were measured and the determinants of swimming velocity were analyzed. Swimming velocity, propulsive force, and the other kinematic and kinetic variables did not change significantly ($p < 0.05$) between sections (only the intra-cyclic fluctuation of swimming velocity decreased significantly, $p = 0.005$). The modeling identified the propulsive force, stroke length, and active drag coefficient as the determinants of swimming velocity. Swimming velocity was determined by the interaction of kinematic and kinetic variables, specifically propulsive force and active drag coefficient.

Keywords: performance; swimming analysis; propulsive force; kinematics; user-friendly data; training; sensors; swimming velocity determinants

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Introduction

Sports performance is a multifactorial phenomenon that depends on the interaction between different scientific fields. That is, it is known that physiology (Kenney et al., 2021), biomechanics (Glazier & Mehdizadeh, 2019), nutrition (Holway & Spriet, 2011), and psychology (Brown & Fletcher, 2017) (among others) play a fundamental role in improving performance. Of these, biomechanics receives much attention because researchers, coaches, and practitioners focus on motion analysis. Motion analysis in sports is considered to be the recording of sports movements and the subsequent computation of meaningful parameters describing the movement from raw kinematic data (Ferdinands, 2010). Therefore, the information provided to athletes is considered of great importance for the improvement of their performance.

In the past, motion analysis in sports was often based on video analysis (Barris & Button, 2008; Shih, 2017). However, due to the time-consuming process of data acquisition and handling (Mooney et al., 2015), researchers are choosing a different method. Nowadays, the use of wearables (i.e., any technological device that can be worn or used as an accessory) is becoming a major approach. Wearables detect sport-specific movements and quantify sports demands that other monitoring technologies may not detect (Chambers et al., 2015; Marković et al., 2021). In the case of swimming, the limitations of video analysis are even more challenging because the cameras are mounted in an aquatic environment. Thus, using wearables consumes less time, provides immediate feedback, and allows data recording without the restriction of distance (Morais et al., 2022d). Additionally, wearables allow the delivery of more comprehensive data to coaches and, consequently, immediate feedback to swimmers.

Swimming velocity depends on the interaction between propulsive and resistive forces (i.e., drag) (Toussaint & Beek, 1992). The literature reports substantial information on the drag of swimmers, indicating that swimmers who have a better hydrodynamic profile are more likely to perform better (Barbosa et al., 2019; Morais et al., 2021b; Narita et al., 2017). However, less information can be found on the swimmers' propulsion despite the theoretical idea that greater propulsion leads to faster swimming velocities. Nonetheless, based on experimental setups, it has been reported that faster stroke frequencies lead to greater propulsive force (Koga, 2020), and greater propulsive force leads to faster swimming velocity (Morais et al., 2020a). It must be highlighted that these experimental findings were only possible based on wearables that allow the swimmers to perform "freely", i.e., without any mechanical restriction. Moreover, it has been argued that increasing propulsion by itself or reducing drag alone may not provide better performance (Morais et al., 2022b). That is, swimmers must generate a great propulsive force while maintaining the "best" possible hydrodynamic position to take advantage of the achieved propulsion and reduce drag as much as possible. It was recently reported that the active drag coefficient (C_{DA}) is the variable that best represents the hydrodynamics of swimmers (Morais et al., 2023). Additionally, the authors mentioned that the C_{DA} can be estimated based on drag or propulsive measurements (which in the past was estimated only through drag measurements)

(Morais et al., 2023). Therefore, in addition to the advantages of using wearables in general, and for propulsive force in particular, researchers and coaches can also obtain access to the C_{DA}.

The literature on swimming, specifically on maximum trial measurements, usually reports data based on the average of that same maximum trial (Barbosa et al., 2019; Figueiredo et al., 2016). However, it was argued that the average of a set of variables may not provide accurate insights about a given performance (Fernandes et al., 2022; Morais, Marinho et al., 2022). In elite-level swimmers competing in European Championships (long-course, i.e., 50 m length, swimming pool), it was observed that sprinting swimmers tend to decrease their swimming velocity along a short-distance event (Morais et al., 2022b). It was also observed that the stroke frequency and the stroke length tended to increase over the race (Morais et al., 2022b). Similar findings were observed in high-level swimmers during 25 m maximum trials (Morais et al., 2020a; Fernandes et al., 2022). Thus, it seems that, despite the length of the swimming pool (i.e., 50 or 25 m), there is a tendency for swimming velocity to decrease in maximal trials or sprinting events. However, little is known about the propulsive force of swimmers and its implication in improving swimming velocity. Moreover, and as previously mentioned, drag is one of the most important topics in swimming. Once again, drag-related variables (i.e., active drag or C_{DA}) are also typically measured as an average across a trial rather than across sections or strokes (Morais et al., 2013; Moreira et al., 2014). Consequently, little is known about the changes that may occur in the swimmers' hydrodynamics and their effect on their performance.

The aim of this study was to understand the variation of a set of kinematic and kinetic variables between two swimming sections and their relationship to swimming velocity. It was hypothesized that the propulsive force and the C_{DA} would have a meaningful effect on the velocity of swimmers.

Materials and Methods

The sample consisted of 15 young adult recreational swimmers (8 males: 20.84 ± 2.03 years, 73.87 ± 7.95 kg of body mass, 176.00 ± 7.21 cm of height, 174.81 ± 7.84 cm of arm span; 7 females: 20.13 ± 1.90 years, 69.14 ± 7.38 kg of body mass, 170.00 ± 7.34 cm of height, 171.21 ± 7.01 cm of arm span; all pooled together: 20.51 ± 1.93 years, 71.66 ± 7.80 kg of body mass, 173.20 ± 7.66 cm of height, 173.13 ± 7.43 cm of arm span). The participants were selected from a swimming lessons program. For three months prior to data collection, swimmers were in a twice-weekly (three hours) swimming lesson program. They had a previous background in swimming (4.07 ± 2.15 years of practice). All procedures were in accordance with the Declaration of Helsinki regarding human research, and the University Ethics Board approved the research design (N.º 72/2022).

Anthropometrics

Body mass (BM, in kg) was measured on an electronic scale (Tanita, MC 780-P, Tokyo, Japan) with minimal clothing. Height (H, in cm) was collected using an electronic stadiometer (Seca, 242, Hamburg, Germany). Arm span (AS, in cm), hand surface area (HSA, in cm^2), and frontal surface area (FSA, in cm²) were measured by digital photogrammetry. For the AS measurement, swimmers were placed near a 2D calibration object in an ortho-static position with both arms in lateral abduction at a 90° angle to the trunk. Both arms and fingers were fully extended. The distance between the tips of the third fingers was measured with a dedicated software program (Udruler, AVPSoft, United States) (Morais et al., 2020b). For HSA measurement, the swimmers' palms were photographed with a digital camera (Sony a6000, Tokyo, Japan). Each HSA was calculated using a dedicated software program (Udruler, AVPSoft, United States) (Morais et al., 2020b).

For FSA measurement, the swimmers were photographed with a digital camera (Sony a6000, Tokyo, Japan) in the transverse plane next to a 2D calibration object to calibrate the image. While swimming, swimmers change their FSA. It is assumed that such a change has a direct effect on the hydrodynamics of the swimmers (Morais et al., 2020c). For this purpose, the swimmers were instructed to lie down on a bench wearing their swimsuits, cap, and goggles. Their lower trunk was supported on the bench so that swimmers could lean on the upper part of their trunk. Swimmers were photographed in the following positions: (i) right hand catch; (ii) right hand insweep; (iii) right hand exit and left hand catch; (iv) left hand insweep; and (v) left hand exit and right hand catch (Morais et al., 2020c). This was done to represent the duration of an entire stroke cycle. In this case, the beginning and end of each stroke cycle was considered the consecutive entry of the right hand into the water. Then, each FSA position was measured by digital photogrammetry as previously mentioned (Morais et al., 2020b). Values at each position were interpolated using a cubic spline from which the FSA values were calculated at each percentage point (each 5%) of the stroke (Figure 1). This was used to calculate the C_{DA} (see the "Active Drag Coefficient" section).

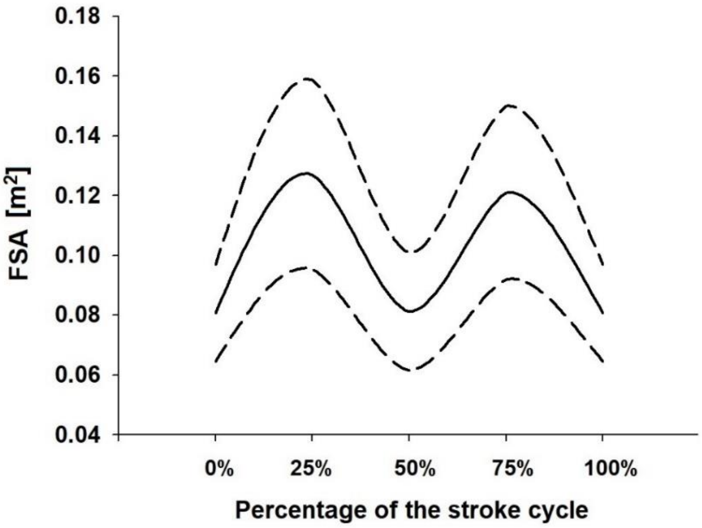

Figure 1. Frontal surface variation (FSA) during an entire stroke cycle. Solid line represents the average, and dashed lines represent the 95% confidence intervals.

Research Design of In-Water Data

After a standardized warm-up, swimmers were instructed to perform an all-out 25 m trial in front-crawl with a push-off start. They were advised not to breathe while performing between the 10th and the 20th meter marks to avoid changes in their stroke coordination or technique (McCabe et al., 2015). Between the 10th and the 20th meter marks, two sections were analyzed: (i) S10–15 m: distance between the 10th and 15th meter marks; and (ii) S15–20 m: distance between the 15th and 20th meter marks. In each section of the race, the average of a set of variables was measured.

Kinematics

To measure swimming velocity, the string of a speedometer (SpeedRT, ApLab, Rome, Italy) was attached to the swimmers' hip (Morais et al., 2022c). The speedometer calculated the displacement and velocity of the swimmers at a rate of 100 Hz. Afterwards, data were imported into a signal-processing software program (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, CA, USA). The signal was handled with a Butterworth 4th-order low-pass filter (cut-off: 5 Hz) upon residual analysis. A GoPro Hero 7 video camera (at a sampling rate of 60 Hz) was synchronized to the speedometer to film the swimmers' performance in the sagittal plane to identify the passing moment of each section. The swimming velocity (in m/s) was obtained from the software in each section of the race (i.e., S10–15 m and S15–20 m). The intra-cyclic fluctuation of swimming velocity (*dv*, in %) was calculated as the coefficient of variation (CV: CV = (one standard deviation)/mean) · 100) (Barbosa et al., 2005). The stroke frequency (SF, in Hz) was measured by calculating the number of cycles per unit of time from the time required to complete one full cycle (f = 1/t), and afterward converted to Hz. A complete stroke cycle was considered to end at the moment of consecutive entry of the right hand into the water. The stroke length (SL, in m) was computed as SL = v/SF, in which v is the swimming velocity (in m/s), and SF is the stroke frequency (in Hz) (Craig & Pendergast, 1979). The stroke index (SI, in m^2/s) was used as a swimming efficiency indicator (Costill et al., 1985). It was calculated as SI = v · SL, in which SI is the stroke index (in m^2/s), v is the swimming velocity (in m/s), and SL is the stroke length (in m). Figure 2 (panel A) represents the speedometer setup.

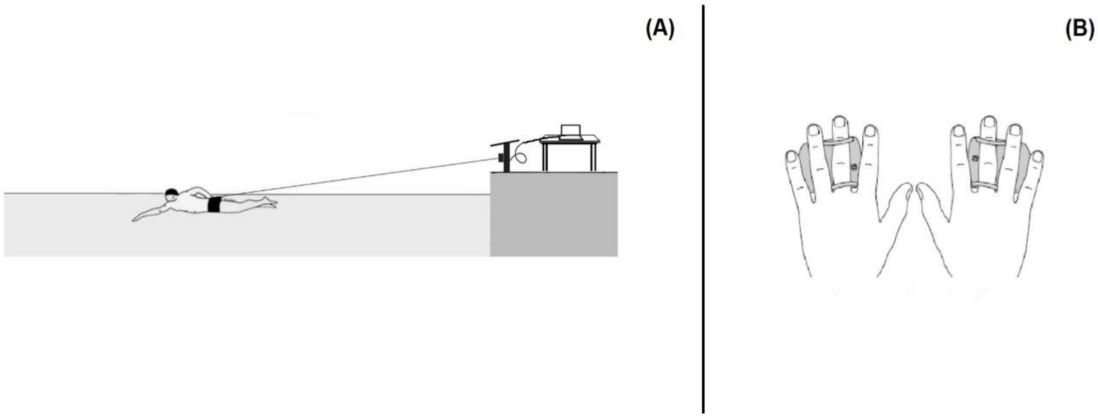

Figure 2. Panel (A)—speedometer setup for the swimming velocity measurement. Panel (B)—placement of the sensors for propulsive force measurement.

Kinetics

Propulsive Force

The propulsive force was measured with SmartPaddles® (Trainesense, Tampere, Finland). These are wearable sensors that measure a set of kinetic and kinematic variables during a swimming stroke (Marinho et al., 2022). It consists of three parts: the SmartPaddles®, the PoolShark Session Manager mobile application for recording, and the Analysis Center (https://sharksensors.com/) for analysis and data storage. The SmartPaddles® sensor unit is attached to the swimmer's hand with silicon straps (Figure 2—panel B). It records the applied force using two pressure sensors and movement with 9-axis IMU. The device uses a sampling frequency of 100 Hz. The PoolShark Session Manager acts as a user interface between a mobile device and the SmartPaddles®. It is used to manage the recording and upload the data to the Analysis Center. The Analysis Center automatically analyzes the recordings and visualizes the performance. The main focus of the Analysis Center is to provide instantaneous information to train athletes in the training environment. Furthermore, it also allows downloading the data for further processing. As far as it is known, the SmartPaddles® calculation algorithm has not been published yet. The SmartPaddles® generates the processed data through the closed Matlab GUI (Graphical User Interface) (Tampere, Finland) developed by the Trainesense Oy (Tampere, Finland). This means that there is no access to SmartPaddles® raw data and the algorithm calculation constants cannot be adjusted.

As mentioned before, swimming velocity was obtained during three consecutive stroke cycles in each section (i.e., S10–15 m and S15–20 m). Consequently, the three corresponding arm-pulls of each upper limb were used. Figure 3 (panel B1—left upper limb; panel B2—right upper limb) shows an example of a swimmer's arm-pulls during the entire trial. Each arm-pull was defined as the time spent between the entry and exit of the hand. For the right (F_{mean_right}, in N) and left (F_{mean_left}, in N) arm-pulls, the mean propulsion was measured. Afterward, the mean propulsive force generated during an entire stroke ($F_{mean\_stroke\ cycle}$, in N) cycle was calculated as (F_{mean_right} + F_{mean_left})/2 (in N). The sum of the two arm-pulls (F_{total}, in N) was calculated to retrieve the total propulsive force generated during a full stroke cycle (F_{mean_right} + F_{mean_left}). The impulse related to each arm-pull was calculated as: $Imp = F \cdot \triangle t$, in which Imp is the impulse (in N·s), F is the propulsive force (in N), and $\triangle t$ is the amount of time the propulsive force was generated (in s).

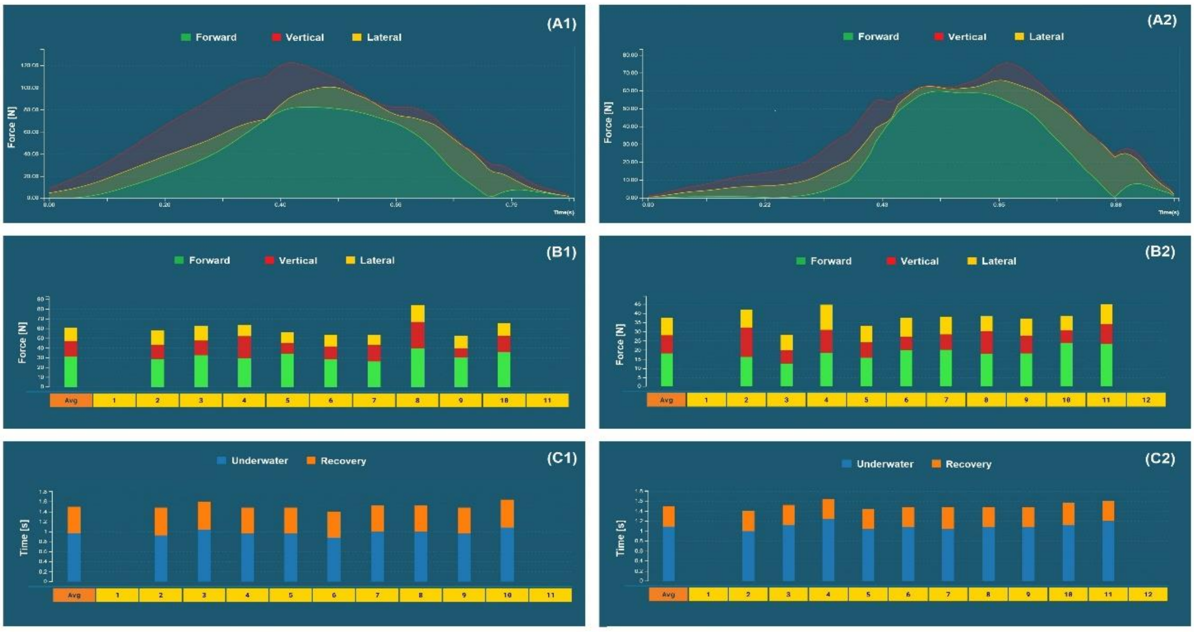

Figure 3. Example of data that can be analyzed in the Analysis Center. Suffixes 1 and 2 correspond to the left and right hand, respectively. Panels (A)—amount and force direction of the average arm-pull. Panels (B)—amount of force by arm-pull. Panels (C)—time spent in each arm-pull (underwater phase) and in recovery (aerial phase).

Active Drag Coefficient (C_{DA})

The C_{DA} was calculated based on inverse dynamics, taking the total propulsive force generated during an entire stroke cycle (Morais et al., 2023). Therefore, the C_{DA} was calculated as C_{DA} = propulsive force/($0.5 \cdot v^2 \cdot \rho \cdot$ FSA), in which C_{DA} is the active drag coefficient (dimensionless), the propulsive force is the amount of propulsive force generated in an entire stroke cycle (sum of both upper limbs, in N), v is the swimming velocity (in m/s), ρ is the water density (assumed to be 997 kg/m^3), and FSA is the frontal surface area (assumed to be the variation verified during one entire stroke cycle, in m^2).

Statistical Analysis

The Shapiro–Wilk test and Levene's test were used to assess the normality and homoscedasticity, respectively. Mean plus one standard deviation was computed as descriptive statistics.

For the v, *dv*, SF, SL, SI, $F_{mean\_stroke\ cycle}$, $Imp_{mean\_stroke\ cycle}$, F_{total}, and C_{DA}, a paired sample *t*-test ($p < 0.05$) was used to verify the difference between the two sections. For the F_{mean_right}, Imp_{right}, F_{mean_left}, and Imp_{left}, a two-way repeated measures ANOVA ($p < 0.05$) was used: (i) arm-pull time effect (difference between S10–15 m and S15–20 m); and (ii) side effect (difference between the right and left upper limbs). In both analyses, a gender effect was tested ($p < 0.05$), revealing a non-significant effect in both analyses. Therefore, data are presented with the two genders grouped together. Cohen's d was used to estimate the pairwise standardized effect sizes and was deemed as: (i) trivial if 0 ≤ d < 0.20; (ii) small if 0.20 ≤ d < 0.60; (iii) moderate if 0.60 ≤ d < 1.20; (iv) large if 1.20 ≤ d < 2.00; (v) very large if 2.00 ≤ d < 4.00; and (vi) nearly perfect if d ≥ 4.00 (Hopkins, 2002).

Hierarchical linear modeling (HLM) was used to identify the determinants of swimming velocity. Two models were tested. In the first model, the differences between genders and the changes over time were tested. In the second and final model, the determinants of swimming velocity were tested (i.e., kinematics and kinetics). The final model considered only the significant determinants. Maximum likelihood estimation was calculated on HLM7 software (Raudenbush et al., 2011).

Results

SmartPaddles and Analysis Center

Figures 3 and 4 represent an example of data from a swimmer, which can be observed in the Analysis Center. Figure 3 reports the propulsive force data (i.e., average orientation, arm-pull by arm-pull propulsive force, and underwater and recovery times). Figure 4 represents an example of the trajectory of a swimmer's hands in the top, side, and back views. The trajectory data corresponds to the average of the total arm-pulls performed by each hand.

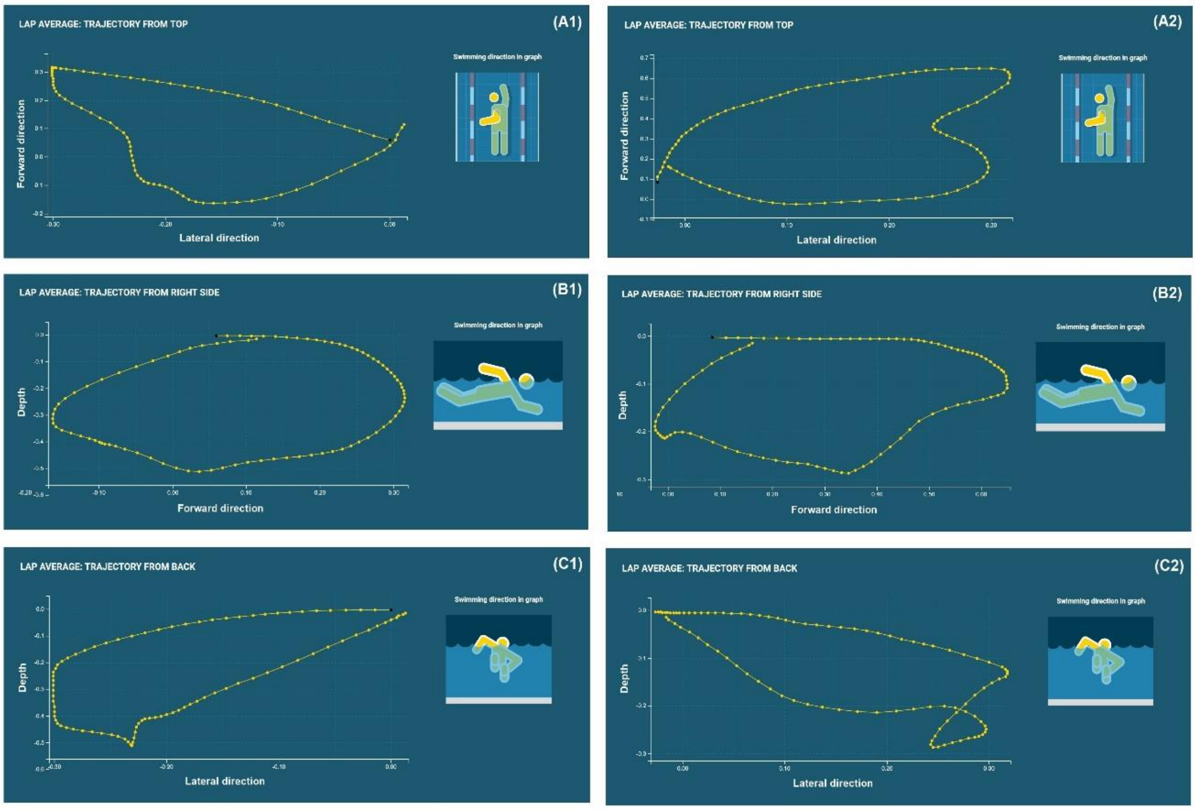

Figure 4. Example of a swimmer's hand trajectory that can be analyzed in the Analysis Center. Suffixes 1 and 2 correspond to the left and right hand, respectively. Panels (A)—top view of the arm-pulls. Panels (B)—side view of the arm-pulls. Panels (C)—back view of the arm-pulls.

Experimental Results

Table 1 presents the descriptive data (mean ± one standard deviation—1SD) of the propulsive force and impulse generated by each hand in each section. Inferential analysis revealed a non-significant time and side effect, as well as a non-significant time X side interaction for both variables. This shows that the propulsive force and impulse did not change significantly between sections, and non-significant differences were observed between hands. Notwithstanding, both variables showed higher values at S15–20 m than at S10–15 m (but with a trivial effect size).

Table 1. Descriptive data (mean ± one standard deviation—1SD) of the propulsive force generated by hand in each section. It also presents the time effect (arm-pull difference between sections), side effect (difference between the propulsive force generated by both hands), and the respective interaction.

	Mean ± 1 SD		**Time**	**Side**	**Interaction Time X Side**	
	S10–15 m	**S15–20 m**	**F-Ratio (*p*)**	**F-Ratio (*p*)**	**F-Ratio (*p*)**	**d [Descriptor]**
F_{mean_right} [N]	23.87 ± 4.87	24.17 ± 5.13	0.472 (0.498)	1.794 (0.191)	0.002 (0.961)	0.06 [trivial]
F_{mean_left} [N]	27.03 ± 7.27	27.29 ± 8.15				0.03 [trivial]
Imp_{right} [N·s]	19.82 ± 5.00	20.02 ± 5.49	0.520 (0.477)	1.249 (0.273)	0.044 (0.835)	0.04 [trivial]
Imp_{left} [N·s]	22.45 ± 6.61	22.62 ± 7.58				0.02 [trivial]

F_{mean_right}—mean propulsive force generated by the right hand; F_{mean_left}—mean propulsive force generated by the left hand; Imp_{right}—impulse generated by the right hand; Imp_{left}—impulse generated by the left hand; *p*—significance value.

Table 2 presents the descriptive data (mean ± one standard deviation—1SD) of the kinematic and kinetic variables by section. It also presents the comparison between sections. Swimmers slightly increased their swimming velocity between sections (non-significantly with a trivial effect size). The same was observed for the other kinematic and kinetic variables. The C_{DA} slightly decreased between sections (trivial effect size). The *dv* was the only variable that presented a significant change (decrease, i.e., suggesting better performance but with a small effect size).

Table 2. Descriptive data (mean ± one standard deviation—1SD) of all variables measured and the *t*-test comparison between sections.

	Mean ± 1 SD					
	S10–15 m	**S15–20 m**	***t*-Test (*p*)**	**Mean Difference**	**95CI**	**d [Descriptor]**
v [m/s]	1.21 ± 0.16	1.22 ± 0.17	−1.391 (0.186)	−0.012	−0.031 to 0.007	0.06 [trivial]
***dv* [%]**	33.82 ± 15.22	25.59 ± 13.15	3.280 (0.005)	8.241	2.853 to 13.629	0.58 [small]
SF [Hz]	0.83 ± 0.11	0.83 ± 0.13	−0.255 (0.803)	−0.003	−0.025 to 0.020	0.00 [trivial]
SL [m]	1.48 ± 0.20	1.49 ± 0.24	−0.737 (0.473)	−0.015	−0.059 to 0.029	0.05 [trivial]
SI [m^2/s]	1.80 ± 0.38	1.83 ± 0.43	−1.031 (0.320)	−0.037	−0.115 to 0.040	0.07 [trivial]
$F_{mean\_stroke\ cycle}$ [N]	25.45 ± 4.11	25.73 ± 5.34	−0.585 (0.568)	−0.274	−1.279 to 0.731	0.06 [trivial]
$Imp_{mean\_stroke\text{-}cycle}$ [N·s]	21.03 ± 4.68	21.32 ± 5.76	−0.570 (0.578)	−0.288	−1.370 to 0.794	0.06 [trivial]
F_{total} [N]	50.91 ± 8.24	51.46 ± 10.68	−0.583 (0.569)	−0.547	−2.558 to 1.464	0.06 [trivial]
C_{DA} [dimensionless]	0.76 ± 0.24	0.75 ± 0.27	0.112 (0.912)	0.002	−0.035 to 0.039	0.04 [trivial]

v—swimming velocity; *dv*—intra-cyclic variation of swimming velocity; SF—stroke frequency; SL—stroke length; SI—stroke index; $F_{mean\_stroke\ cycle}$—mean propulsive force (average of both hands) of the stroke cycle; $Imp_{mean\_stroke\ cycle}$—mean impulse (average of both hands) of the stroke cycle; F_{total}—total propulsive force (sum of both hands) of the stroke cycle; C_{DA}—active drag coefficient.

Table 3 presents the fixed effects of the final computed model, keeping only the significant determinants. The C_{DA} was the variable with the highest contribution to the swimming velocity. A one-unit increase in the C_{DA} imposed an increase of 0.593 m/s (95CI: −0.636 to −0.550; $p < 0.001$) in the swimming velocity. That is, an increase of the C_{DA} promoted a negative and significant effect on the swimming velocity. The other determinants had a positive (and significant) effect on the swimming velocity. That is, a larger SL and greater F_{mean} (right and left) led to a faster swimming velocity.

Table 3. Fixed effects of the final model including standard errors and (SE) and 95% confidence intervals (95CI).

Parameter Fixed Effect	Estimate (SE)	95CI	*p*-Value
SL [m]	0.067 (0.025)	0.018 to 0.116	0.014
C_{DA} [dimensionless]	−0.593 (0.022)	−0.636 to −0.550	<0.001
F_{mean_right} [N]	0.007 (0.001)	0.005 to 0.009	<0.001
F_{mean_left} [N]	0.008 (0.001)	0.006 to 0.010	<0.001

SL—stroke length; C_{DA}—active drag coefficient; F_{mean_right}—mean propulsive force of the right hand; F_{mean_left}—mean propulsive force of the left hand.

Discussion

The aim of this study was to understand the variance of a set of kinematic and kinetic variables between two swimming sections and their relationship to swimming velocity. Swimming velocity did not significantly change between sections. The same was observed in the propulsive force with a non-significant side effect as well (i.e., difference between right and left arm-pulls). Likewise, the other kinematic and kinetic variables did not change significantly between sections, except for the *dv* (which significantly decreased between sections). Moreover, hierarchical modeling revealed that the SL, C_{DA}, and the propulsive force of both hands were the main determinants of the swimming velocity, with the C_{DA} being the greatest contributor.

SmartPaddles and Analysis Center

Several studies mention the advantages of using wearables in swimming and other sports, regardless of the type of variables measured and monitored (Dadashi et al., 2012; Marković et al., 2021). However, regardless of whether it is based on IMU's or other sensors, data handling (after data collecting) may not be user-friendly for coaches and swimmers. That is, data often need to be filtered and manipulated to be presented to coaches and swimmers. Indeed, studies using wearables indicate that data often have noise that needs to be filtered out (Chambers et al., 2015; Fusca et al., 2018). This process might be time-consuming and not user-friendly for non-experts with data handling such as coaches and swimmers. Therefore, having wearables that can be paired with operating systems that allow the presentation of filtered data to coaches and swimmers is an important step in the training process. As previously mentioned, the set of sensors used in this study is based on a system that includes the sensor units, an application for recording, and an analysis and data storage application for visualization (Marinho et al., 2022). Consequently, coaches and swimmers can visualize the propulsive force time-series (Figure 3—panels A), the average of all arm-pulls performed (Figure 3—panels B), and the time spent in the underwater and recovery phases (Figure 3—panels C). Moreover, as the sensor units are based on IMU's, the hand's path can also be visualized from several perspectives (Figure 4). This visualization allows both coaches and swimmers to better understand the potential difficulties in their stroke mechanics. Indeed, information about the path of the swimmers' hand is of great importance for improving performance (Sanders et al., 2021).

Propulsive force in swimming can be experimentally and directly measured based on pressure sensors or IMU's (Koga et al., 2022; Marinho et al., 2022; Morais et al., 2020a). It can also be indirectly measured by tethered swimming (Samson et al., 2019). Despite all the methods, there is still no gold-standard method to measure propulsive force in swimming. Notwithstanding, it should be mentioned that the sensor units used in the present study had a high agreement with a commonly used pressure sensor system (Marinho et al., 2022).

Experimental Results

Most studies that analyze propulsive force in swimmers (as it relates to swimming velocity) tend to use the average of a given trial for further analysis (Kadi et al., 2022; Koga et al., 2022); however, in sports, an intravariability occurs (Preatoni et al., 2013). That is, athletes may not always reproduce a given motion in the exact same way. In swimming, this phenomenon may be even greater due to the unstable conditions of the aquatic environment (Bideault et al., 2013). Therefore, to have a deeper insight, researchers and coaches can measure a given variable in different swimming pool sections as it is done in a race analysis context (Morais et al., 2022c) or in a stroke-by-stroke analysis during a given trial (Fernandes et al., 2022; Morais et al., 2021a). In the present study, the researchers chose to analyze the variables between sections for convenience and because the sample consisted of recreational swimmers rather than high-level swimmers. The data revealed that the propulsive force of the swimmers in front-crawl did not differ between the sections and did not present a significant side effect (i.e., differences between right and left hand). The literature lacks information on the propulsive force variation during trials. Notwithstanding, Morais et al. (2020a) observed that, at least in high-level swimmers, propulsive force at maximum swimming velocity tended to decrease in a stroke-by-stroke analysis. However, the authors (Morais et al., 2020a) observed a significant side effect (with a small effect size—based on the cut-off values of this study), which was not found in the present study. Therefore, based on sample demographics or other characteristics (such as dry-land strength or motor control), swimmers may or may not have a significant difference in the mean propulsive force between sides. This is a phenomenon that needs to be further studied, as well as its implications for swimming performance.

The activity observed in swimming velocity (and remaining kinematic variables) was the same as in the propulsive force, i.e., it did not significantly change between sections. In maximal trials or official sprinting events, swimming velocity tends to decrease significantly throughout the trial or front-crawl race in trained swimmers (Morais et al., 2020a; Morais et al., 2022b). As this sample was composed of recreational swimmers, it seems that they presented an opposite profile when performing a maximal trial. As mentioned previously, swimming velocity and propulsive force did not change significantly between sections. The only variable that presented a significant difference between sections was the *dv*, in which a decrease was observed. The *dv* is considered an efficiency proxy, in which smaller values are usually related to better performances (Barbosa et al., 2019; Figueiredo et al., 2016). However, such an assumption is based on the average values of the entire trial. New approaches in swimming research are arguing that smaller values observed in the *dv*, at least in front-crawl, may not always be related to better performances and vice-versa (Fernandes et al., 2022). Although swimming with greater gross efficiency may lead to lower energy expenditure (Ganzevles et al., 2019), it is argued that swimmers can use different patterns of stroke mechanics (related to swimming efficiency) to maximize swimming velocity, at least in maximal trials or events (Fernandes et al., 2022). Indeed, it can be argued that, in maximal trials or sprint events, swimmers are not concerned about saving energy. Therefore, swimmers can adopt a strategy based on generating greater propulsive forces and less efficient technique (Fernandes et al., 2022). The C_{DA} also decreased slightly (but not significantly) between sections. As far as it is known, this is the first study that indicates the measurement of C_{DA} within the same trial. It was previously reported that, during swimming, FSA changes (Morais, Sanders et al., 2020; González-Ravé et al., 2022) and, consequently, active drag changes (Morais et al., 2020c). Therefore, it can be suggested that the C_{DA} can also change during swimming. The data of this study corroborates this assumption. Based on inverse dynamics, taking the propulsive force generated by the swimmers, their swimming velocity, and their FSA variation, it was possible to calculate the C_{DA} in each section. Overall, it can be stated that the increase in swimming velocity between sections (although not significant) may be related to the increase in propulsive force concurrently with the decrease observed in the *dv* and C_{DA}.

Hierarchical linear modeling was used to identify the determinants of swimming velocity. As male and female swimmers were tested together and repeated measurements were performed, the effects of gender and time were tested, respectively. Gender and time revealed a non-significant effect. This indicates that men and women can be grouped together to identify the determinants of swimming velocity. Moreover, a significant time effect for the swimming velocity test was not identified. This indicates that swimming velocity did not change significantly between sections (as previously tested). Thus, it can be stated that recreational swimmers do not have a profile similar to high-level swimmers, where a significant decrease in swimming velocity is observed between sections in a maximal trial or sprinting event (Morais et al., 2022b). The final model revealed SL, F_{mean_right}, F_{mean_left}, and C_{DA} as significant determinants of swimming velocity. Regarding SL, current data indicate that swimmers who were able to cover a greater distance per stroke are more likely to achieve faster swimming velocities, which is a well-known fact in swimming (Barbosa et al., 2019; Figueiredo et al., 2016). Regarding propulsive force, theoretical models based on numerical studies indicated that greater levels of propulsive force led to faster swimming velocities (Cappaert et al., 1995; Loebbecke & Mittal, 2012). More recently, experimental studies have demonstrated this phenomenon, finding that higher values of propulsive force led to faster swimming velocities (Koga et al., 2020; Morais et al., 2020a). Here, it could even be argued that a greater propulsive force might also allow for a larger SL and, hence, a faster swimming velocity. Indeed, it has been argued that propulsive force may play a key role in the SF–SL interaction to increase swimming velocity (Morais et al., 2022a). The C_{DA} was also kept as a significant determinant of swimming velocity. The literature is committed to showing that hydrodynamics plays a fundamental role in the swimmers' performance, where swimmers who present smaller values are more likely to present better performances (Morais et al., 2021b; Marinho et al., 2020).

In the past, due to equipment constraints, it was more difficult to measure propulsive force directly and, hence, test it as a determinant of swimming velocity. The data of the current study indicates that swimming velocity was determined by the interaction of kinematics (SL) and kinetics (propulsive force and C_{DA}, i.e., hydrodynamics). This is in line with the literature, which highlights swimming as a holistic phenomenon. Notwithstanding, it should be mentioned that swimmers can achieve faster swimming velocities by generating propulsive forces while reducing resistive forces (Toussaint & Beek, 1992). These findings reveal that both propulsion and C_{DA} are significant determinants of swimming velocity. Recently, it has been reported that swimmers can experience misalignments when producing propulsive force, which will lead them to have a larger FSA area and, therefore, a greater resistive force (Morais et al., 2020c). Consequently, they can be under a higher resistive force immediately after they generate propulsive force, promoting a decrease in their swimming velocity. Therefore, it can be suggested that there is no point in generating greater levels of propulsive force if immediately afterward one does not adopt a position that is as hydrodynamic as possible, i.e., decreases the water resistance.

As the main limitations of the present study, it can be considered that: (i) these data are suitable only for sprint trials or events, i.e., maximal swimming velocity; (ii) an indicator of the swimmers' motor control was not measured, for example, the index of coordination. This may bring a deeper insight on the relationship between the swimmers' velocity and the propulsive force and C_{DA}; and (iii) FSA variation was measured based on land positions simulating the key-moments of the swimming stroke. It should be stated that, whenever possible, researchers are advised to measure FSA based on an in-water approach (González-Ravé et al., 2022; Morais et al., 2020c). Future studies should focus on understanding the relationship between propulsive force and swimming velocity at different paces or intensities. Moreover, whenever suitable, a stroke-by-stroke analysis should be performed to understand the variance of these variables and their relationship to swimming velocity.

Conclusions

This study concludes that recreational swimmers did not significantly change their swimming velocity between the two sections. The same activity was observed in the propulsive force and in the other kinematic and kinetic variables measured, except for the *dv*. Hierarchical modeling revealed that swimming velocity was determined by the interaction of kinematic (SL) and kinetic variables (F_{mean_right} and F_{mean_left}—propulsive force; C_{DA}—resistive force). Coaches and swimmers should be aware of the importance of balance in both generating propulsive forces and decreasing resistive forces.

Study 3. Comparison of the active drag and passive drag coefficients at the same swimming speed through experimental methods

Abstract

This study used a complete experimental methodology to determine the resistive forces in crawl swimming at the same speed ((i.e., 1.00, 1.05, 1.10 m/s, etc.). In 10 proficient non-competitive adult swimmers (seven men and three women), the drag coefficient (C_D) was compared and the difference between using the technical drag index (TDI) with drag (D, passive or active) or with its respective C_D 's. Measurements of active drag (D_A), passive drag (D_P) and C_D (C_{DA} and C_{DP}) were carried out. The TDI was calculated as a measure of swimming efficiency and the frontal surface area (FSA) obtained in active conditions. The active FSA was 20.73 ± 5.56% greater than the passive FSA (large effect size), the propulsion was 58.29 ± 69.61% greater than drag and C_{DA} was 24.60 ± 46.55% greater than C_{DP} (moderate effect size). TDI was significantly lower, but with a small effect size when measured with C_D values compared to drag. TDI_D vs TDI_{CD} revealed strong agreement (> 80% of plots were within IC95). This study concludes that proficient swimmers presented a C_{DA} greater than the C_{DP}, but with strong agreement between them, probably due to FSA during active conditions. C_D data appears to be a more absolute indicator of drag than TDI.

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

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Introduction

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

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

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

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

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

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

Methods

Participants

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

Research design

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

Measurement of the active drag coefficient (C_{DA})

The C_{DA} was calculated based on equation (2). Studies have shown that propulsion data can be used to replace drag data in such equation to calculate the C_{DA} (Havriluk, 2007; Morais et al., 2023). Propulsion was measured with wearable sensors (SmartPaddles®, Trainesense, Tampere, Finland) (Lopes et al., 2023). The sensors were attached to the swimmers' hands with silicon straps. The average propulsion of both upper limbs' arm-pulls performed between the 10th and 20th meter marks was retrieved from the database PoolShark Session Manager (https://sharksensors.com/). Afterwards, the total propulsion (P_{total}, in N) was calculated as the sum of the right and left arm-pulls. At the same time, the participants were attached to a string of a speedometer (SpeedRT, ApLab, Rome, Italy) to measure the swimming speed (in m/s). Afterwards, the speed-time series were imported into a signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, USA). The signal was handled with Butterworth 4th order low-pass filter (cut-off: 5Hz). A video camera (GoPro Hero Black 7, USA) was placed in a fixed position in the mid-section of the swimming pool to record the swimmers in the sagittal plane and identify the hand entry. By doing this, it was possible to synchronize propulsion and speed data.

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

Measurement of the passive drag (D_P) and passive drag coefficient (C_{DP})

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

Technique drag index

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

$$TDI = \frac{k_A}{k_P} \qquad (2)$$

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

Statistical analysis

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

Results

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

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

	Mean	**SD**	**95CI**	**Relative Difference [%]**
Swimming speed [m/s]	1.25	0.14	1.15 to 1.35	
FSA_{active} [m²]	0.0982	0.0094	0.0915 to 0.1050	20.73 ± 5.56
$FSA_{passive}$ [m²]	0.0793	0.0120	0.0708 to 0.0879	
Propulsion [N]	52.48	9.78	45.48 to 59.48	58.29 ± 69.61
Passive drag [N]	37.99	14.38	27.71 to 48.28	
C_{DA} [dimensionless]	0.71	0.22	0.56 to 0.87	24.60 ± 46.55
C_{DP} [dimensionless]	0.60	0.12	0.51 to 0.68	
TDI_D [dimensionless]	1.58	0.73	1.06 to 2.11	19.69 ± 4.83
TDI_{CD} [dimensionless]	1.25	0.49	0.90 to 1.60	

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

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

	t-test (p-value)	**MD**	**95CI**	**d [descriptor]**
FSA_{active} vs $FSA_{passive}$ [m²]	14.69 (<0.001)	0.0189	0.0160 to 0.0218	1.88 [large]
Propulsion vs Drag [N]	2.67 (0.026)	14.48	2.20 to 26.77	1.18 [moderate]
C_{DA} vs C_{DP} [dimensionless]	1.42 (0.189)	0.12	-0.07 to 0.30	0.62 [moderate]
TDI_D vs TDI_{CD} [dimensionless]	-4.24 (0.002)	-0.34	-0.52 to -0.16	0.53 [small]

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

Figure 1 depicts the Bland-Altman analysis of the C_{DA} against the C_{DP} (panel A), and the TDI_D against the TDI_{CD} at the same speed. In both cases, more than 80% of the plots were within the 95CI revealing a strong agreement between variables.

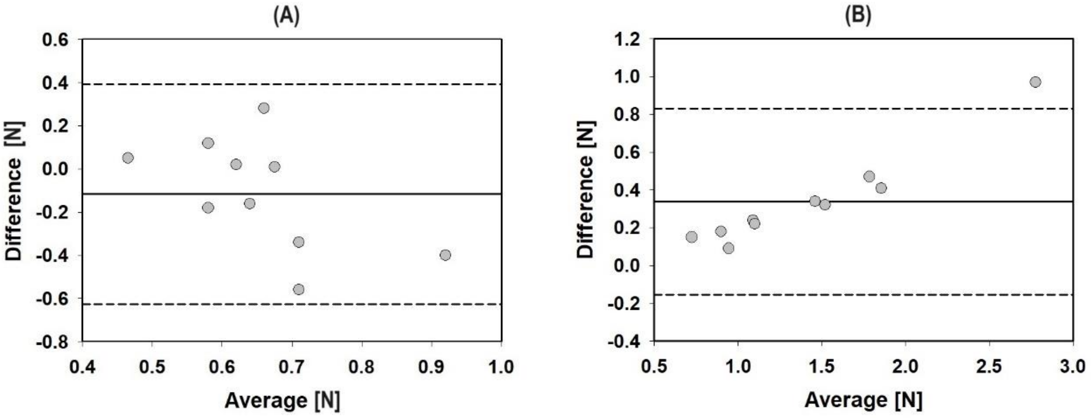

Figure 1. Bland Altman plots of the C_D's (panel A) and the TDI (panel B). Dash lines refer to the 95% confidence intervals.

Discussion and Implications

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

The methods used to determine C_D in both active and passive conditions are commonly reported in the literature (Gatta et al, 2016; Lopes et al., 2022; Vilas Boas et al., 2010). Regarding the active condition, the C_{DA} was calculated based on equation (1) in agreement with the fact that data related to propulsion can be used to replace the drag data in this equation to calculate the C_{DA} (Havriluk, 2007; Morais et al., 2023). The swimmers' C_{DP} was calculated based on the same equation where the drag value was obtained by a passive towing method (Cortesi et al., 2024; Scurati et al., 2019). This was done at the same speed measured while swimming during a maximal trial. Literature is prone on discussing the methods used to measure drag (Havriluk, 2007). There are four methods to measure D_A: (i) measurement of active drag (MAD); (ii) small perturbation method (SPM), also known as velocity perturbation method (VPM); (iii) assisted towing method (ATM), and; (iv) measurement of residual thrust (MRT) (Lopes et al., 2022). Overall, it was considered that despite there is no agreement among methods, they all measure the same phenomenon but in a different way (Lopes et al., 2022).

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

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

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

Conclusions

This study concludes that proficient swimmers showed a larger C_{DA} than C_{DP} but with a strong agreement between them. This can be due to the FSA variation during the active conditions. It seems that the TDI, as a swimming efficiency indicator, may be overestimated when using the absolute values of drag rather than their respective C_D's.

Chapter 4. General Discussion

Overall, the main objectives of this thesis were to: (i) systematically review the state of the art about the methods used to measure D_A in swimming; (ii) understand the variation of a set of kinematic and kinetic variables between two swimming sections and their relationship with swimming speed (where C_{DA} was included), as well as understand the advantages of using wearables to measure propulsion in swimming, and; (iii) compare the C_{DP} with C_{DA} at the same speed.

In swimming, the study of the force that promotes the swimmer's displacement and the force of the water that is exerted on the swimmer's body is essential to better understand the biomechanical needs that determine an efficient swimming technique and to identify areas for improvement in performance. Understanding the interaction between the force generated by the swimmer and the resistance of the water is fundamental to optimizing swimming technique, minimizing drag and maximizing propulsion. In this case, hydrodynamics is one of the most studied areas in swimming. The starting point of this thesis was to carry out a systematic narrative review based on the description of numerical and experimental methods that are regularly used to measure/evaluate D_A (active resistive forces) in swimming (Study 1). Our research concluded that for D_A there are significantly fewer numerical studies (9.33%) than experimental studies (90.67%) since the initial record (1974). This is because D_A, as a dynamic phenomenon, is too complex to be studied numerically. Furthermore, D_A is greater in adults than in children and greater in men than in women in all age groups. Therefore, it is predictable to say that the study of drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming. However, it is also important to state that although most studies agree among them about these findings, there is disagreement in other ones, especially when it is difficult to define competitive level and age. This divergence concerns three main aspects: 1) study deadline and improvement of methodologies; 2) discrimination of methodologies between factors observed in numerical methods vs. experimental; 3) evidence that drag tends to be non-linear and depends on personal, technical and stylistic factors. Based on the complexity of D_A, the study of this phenomenon must continue to gather new insights so that swimming performance can improve. Indeed, this systematic review clearly indicates that there is no gold standard to measure D_A. That is, studies that compared methods to measure D_A reached the same conclusion: they all measure drag (i.e., the same phenomenon) despite differences between measurements/equipment/protocols; and these is due to the characteristics and specificities of each method. Furthermore, given the critical importance of accurately measuring swimming drag, it is notable that research groups continue to dedicate their efforts to improve measurement methods and technologies, thus highlighting the continued relevance and interest in this area. This information is confirmed by studies such as Cortesi et al. (2024) and Haskins et al. (2023). These very recent studies, like older studies, highlight that in human swimming, D_A is around 1.5 times greater than D_P. Both using new or recent methods that aim to evaluate the D_A profile during front crawl swimming (Cortesi et al., 2024; Haskins et al., 2023). In the study by Cortesi et al. (2024) explored the possibility of estimating D_A based on the "residual buoyancy method" and comparing these values with D_P values and with D_A values estimated using the "planimetric method". These experiments can be carried out in an ecological environment (in pool) using basic instrumentation and a simple set of calculations, like older studies, with the particularity that nowadays they are more simplified and easier to obtain data. In the study by Haskins et al. (2023) the D_A was calculated by subtracting the resistance trainer force data from the stationary load cell force data. Average D_A values over the stroke cycle were calculated for comparison with existing methods. Established D_A, such as VPM, shows agreement in the magnitude of average D_A forces. Both described methods are proposed as a representation of the D_A profile over a complete stroke cycle (Cortesi et al., 2024; Haskins et al., 2023).

Exploring the previous paragraph, it is clear that there are several reasons why the interest in continuously investigating a specific variable, such as measuring swimming drag, may persist over time: (1) Technological Advances: as new technologies and methods measurements become available, researchers may want to explore how these innovations can improve the accuracy or efficiency of existing measurements; (2) Evolution of Theories and Models: as scientific understanding advances, new theories and models may emerge, leading researchers to revisit previous variables with a deeper understanding or from new perspectives; (3) Practical Applications: Improving the measurement of a variable can have significant implications in different areas, such as high-performance sports, sports equipment engineering, optimization of training techniques and development of more efficient materials; (4) Complexity of the Phenomenon: Some variables, such as swimming drag, can be highly complex and multifaceted. Researchers can continue to investigate these variables over time to better understand their nuances and how they interact with other aspects of sports performance; (5) Ongoing Needs: As objectives and demands in the area of interest change, there may be an ongoing need for research and development to meet these new demands.

Regarding the second aim, the propulsion measurement is crucial to understand and improve swimmers' performance (Sanders et al., 2012; Soh & Sanders, 2019). This refers to the force generated by swimmers to push their bodies through the water (Soh & Sanders, 2019; Toussaint & Beek, 1992), and is a fundamental element to achieve speed and efficiency in competitive competitiveness. There are several reasons why measuring propulsion is so important: (1) By measuring propulsion, coaches and swimmers can identify areas of weakness and opportunities for improvement in their swimming technique. This allows for specific adjustments in training to maximize movement efficiency and speed in the water (Sanders et al., 2012; Santos et al., 2021); (2) propulsion is closely linked to the technique of nothingness. Measuring propulsion allows for an objective assessment of the effectiveness of each swimmer's technique, identifying strengths and areas in need of development (van Houwelingen et al., 2017); (3) measuring propulsion allows for objective comparisons between swimmers, helping coaches identify promising talent and understand how different swimming styles compare in terms of efficiency and speed (Morais et al., 2022a; Santos et al., 2021); (4) by tracking propulsion over time, swimmers can monitor their progress and see if changes in technique or training result in measurable improvements (Morais et al., 2022b). Although the importance of measuring propulsion is reliable, traditional assessment methods are limited (Morais et al., 2022b). Fortunately, science along with technology is removing an increasingly important role in accurately measuring swimming propulsion. A common experimental approach involves the use of pressure sensors that can be placed on various parts of the swimmer's body (in swimming applied to the hands) to capture real-time data during movement in the water (Kadi et al., 2022; Santos et al., 2021; Webster et al., 2011). These pressure sensors record forces exerted by the water on the swimmer's body as he swims, allowing a detailed analysis of the propulsion generated by each stroke and/or kick. With this data, coaches and swimmers can gain valuable insights into movement effectiveness and make informed decisions about how to improve swimming technique to improve overall performance (Morais et al., 2023). In this way, athletes can improve their technique, reach faster speeds and excel performance. The use of technologies such as pressure sensors is helping to make this measurement more accurate and accessible, providing valuable insights.

Therefore, before understanding the variation and data that each methodology gives us, it is necessary to validate and agree and analyze the methods (Study 2 and 3), identified in a recent systematic review (Study 1, Appendix I and II). These sensors used in each methodology were compared with others and revealed agreement to understand functional patterns of drag and propulsion, as well as an analysis of the biomechanical causes and efficiency in crawl swimming (Study 3). As other authors indicate, smart technology, such as wearables (sensors), applied to sports analysis is essential for improving performance (Marinho et al., 2022). With the same objective of presenting a new wearable equipment (SmartPaddle®) to measure kinematic and kinetic variables in swimming and understand the agreement of the variable propulsive force with a pressure sensor system. Realizing that SmartPaddle® is a system that records a set of kinematic and kinetic parameters useful daily for coaches (Marinho et al., 2022).

To evaluate propulsion, several pressure sensors have been used to measure this specific force. In study 2, wireless sensors were used and provided the trajectory of the hand. This way it is possible to understand at which moment of the stroke swimmers generate the most force. It consists of three parts: SmartPaddles®, the PoolShark Session Manager mobile application for recording and the Analysis Center for data analysis and storage. The mobile application automatically analyzes recordings and visualizes performance, providing instant insights to coach athletes in the training environment. Furthermore, it also allows you to download the data for further processing. Thus, based on a system that brings together sensor units, an application for recording and a data analysis and storage application for visualization, it was possible to measure and monitor the swimmers' propulsive force with immediate feedback to the swimmers. The same study (study 2) used pressure sensors that are also IMU's. The use of pressure sensors combined with IMU’s to measure swimming propulsion represents an advanced and comprehensive approach to understanding swimmers' movement. These devices not only capture the force exerted by the water on the swimmer's body, but also provide valuable data on the trajectory of the hand in the three planes of space (sagittal, frontal and transverse), enabling a more detailed and accurate analysis of the swimming technique. (Fantozzi et al., 2016; Hamidi Rad et al., 2021; Morais et al., 2022c). This provides a comprehensive understanding of hand movement during each phase of the stroke, from entering the water to exiting. Furthermore, the trajectory of the hand is a fundamental aspect of the swimming technique, as it directly influences the effectiveness of propulsion and the efficiency of the movement (Kadi et al., 2022). A smooth and fluid trajectory, aligned with appropriate biomechanical principles, can result in more efficient propulsion and a reduction in hydrodynamic resistance (Morais et al., 2022c). By analyzing the trajectory of the hand in all three planes, researchers and trainers can examine the angles of attack of the hand in relation to the direction of movement. These angles are critical in determining the effectiveness of propulsion and can be adjusted to optimize the swimmer's performance (Kadi et al., 2022; Santos et al., 2023). Hand trajectory analysis using pressure sensors and IMU’s allows the detection of inappropriate or inefficient movement patterns. For example, excessive variations in hand trajectory may indicate technique problems that result in less effective propulsion or an increase in hydrodynamic resistance (Marinho et al., 2022; Morais et al., 2022c).

As previously mentioned, it is now even clearer that although there is still no consensus on a gold standard method for measuring forces in water, existing tools must imitate, as much as possible, the movement pattern of the body's limbs (Barbosa et al., 2020).

It was also possible to verify that C_{DA} could be estimated from the propulsion (Study 3). From propulsion, it was possible to estimate the C_{DA}, which means that it not only reflects the resistance that a swimmer encounters in the water, but also how the swimmer is interacting with the aquatic environment to overcome this resistance (Morais et al., 2024c; Morais et al., 2023). C_{DA} should be the variable suggested as a standard variable to characterize the hydrodynamic profile of swimmers due to its ability to provide a comprehensive measure of swimming efficiency (Morais et al., 2023). In contrast to other measures such as propulsion efficiency or isolated swimming technique, C_{DA} considers the relationship between the propulsion generated by the swimmer and the hydrodynamic resistance he or she faces, offering a more complete view of hydrodynamic performance (Morais et al. al., 2024c; Morais et al., 2023). By using C_{DA} as a standard variable, coaches, researchers and swimmers can objectively compare the efficiency of different swimming styles, propulsion techniques and even the effectiveness of equipment like swimsuits. This allows you to identify areas for improvement in swimming technique and training strategies to optimize performance in the water (Morais et al., 2024c). Furthermore, C_{DA} can be a powerful tool for understanding individual differences between swimmers and how factors such as biomechanics, hydrodynamics, and physiology affect swimming performance (Morais et al., 2024c; Morais et al., 2023).

Propulsion and drag (C_{DA}) and kinematic (SL) variables play crucial roles in predicting swimming speed in recreational swimmers (Morais et al., 2023) and talented swimmers (Morais et al., 2024a). The C_{DA}, reflecting the interaction between the swimmer and the aquatic environment and representing both the resistance faced and the efficiency in overcoming it, becomes fundamental. Estimating C_{DA} allows you to understand how swimming technique and propulsion effectiveness directly influence water speed, providing a comprehensive measure of swimming efficiency. On the other hand, kinematic variables, such as stroke width (SL), play a crucial role, as they are directly linked to propulsion effectiveness. An effective stroke, with adequate amplitude, can result in greater propulsion, propelling the swimmer more efficiently. Analysis of these variables not only allows an objective assessment of swimming efficiency, but also helps identify areas for improvement in technique and training, contributing to improvements in individual performance and a deeper understanding of the complexities involved in swimming.

In this study 2, a comparison was carried out between sections of the pool to investigate whether there were variations in drag or C_{DA} throughout the pool. This approach is common in several biomechanical variables, such as speed, SF, DC, *dv*, SI, among others. However, until now, there was no solid evidence that drag or C_{DA} could also vary between pool sections. Surprisingly, the results of this study indicated that there were no significant differences in drag or C_{DA} between different sections of the pool. This suggests that recreational swimmers were able to maintain a consistent hydrodynamic profile throughout the pool, regardless of their location within the pool. This finding is significant because it shows that even in varying conditions, such as different depths or water flows, swimmers can maintain stable hydrodynamic efficiency. This stability in swimming efficiency can be attributed to a combination of factors, including improved swimming technique, biomechanical adaptations, and motor control skills. In the study by Morais et al. (2024b) highlights the importance of understanding the change in C_{DA} over successive stroke cycles in the front crawl and the relationship between swimming speed and C_{DA}. A stroke-by-stroke analysis showed that national level swimmers were able to maintain their hydrodynamic profile during a maximum crawl event (Morais et al., 2024b). Thus, it can be argued that a decrease in swimming speed may be related to a decrease in propulsion (Morais et al., 2024b). Swimming speed and C_{DA} showed an inverse and significant relationship, with lower C_{DA} values resulting in faster swimming speeds (Morais et al., 2024b). This deeper understanding can guide coaches and swimmers in optimizing swimming technique and maximizing performance in the water, contributing to significant advances in the sport.

In this way, experimental studies were carried out on evaluation tools for training control and optimization (studies 2 and 3), as well as seeking to understand the variation of a set of kinematic and kinetic variables between two swimming sections and their relationship with swimming speed (study 2).

Therefore, until now, there is little information about the relationship between the hydrodynamic profile of swimmers, especially at the same swimming speed. The study 3 was carried out to be able to provide deeper knowledge about how the functional patterns of real swimming work in a practical context. And a more concrete investigation into some important results obtained in these studies regarding propulsive force production and drag analysis in swimmers to determine whether drag will be an important data to take into consideration in comparison with C_D (Studies 3). Study 3 compared C_{DP} with C_{DA} at the same speed. Checking whether C_{DA} would be significantly greater than C_{DP} at the same speed, and whether this difference would be like that found between propulsion and drag. In this sense, the hydrodynamic profile of swimmers is a crucial aspect for swimming performance. The comparison between the hydrodynamic profile of swimmers in active and passive movement is an area of research in development and there are still relatively few studies on this. Comparing hydrodynamic profiles in active and passive movement can provide valuable insights into how different factors, such as swimming technique, body posture and fitness, affect a swimmer's efficiency in the water. Furthermore, this comparison can help identify areas for improvement in swimming technique and training, aiming to reduce drag and maximize propulsion. Although there are few studies on this specific comparison, it is a promising area of research that can contribute significantly to understanding and improving swimming performance. As measurement and analysis technology continues to advance, it is likely that more studies will be conducted to explore this question in greater detail.

The lack of knowledge or lack of understanding/confusion that exists around swimming as it is a complex and difficult sport to study, both in terms of technical execution and factors that influence swimmers' performance, such as (1) technique swimming; (2) physiology; (3) aquatic environment; (4) resistive/propulsive forces; (5) biomechanics and (6) external factors such as nutrition, recovery and equipment; It makes swimming more complex, often resulting in complex methodological and technical challenges. Taking this into account, it is difficult to reproduce competition conditions in a laboratory environment and it is difficult to control all the factors that can influence the swimmer's performance (Morais et al., 2021; Morais et al., 2017). However, despite these challenges, researchers continue to investigate swimming using a variety of methods, including biomechanical analyses, physiological studies and performance assessments in real competitions, and this makes cross-sectional studies often as important as longitudinal studies (Barbosa et al., 2023; Mooney et al., 2015). It is still necessary to mention the type of sample, as it may influence the understanding of the data and even its viability. In addition to these technical, physiological and environmental aspects, it is important to consider other factors when studying swimming, such as (1) gender, (2) age, (3) level of experience (competitive or non-competitive), (4) injury history and (5) motivation/psychological factors. It is essential to consider these different aspects and how they interact to influence swimmers' performance and experience (Marinho et al., 2020; Morais et al., 2021; Troup, 1999). This allows for a more comprehensive and accurate understanding of the modality and can inform training strategies, injury prevention and performance optimization (Marinho et al., 2020). For example, the lack of in-depth knowledge about the physical changes of young swimmers seems to arise from some ethical issues when children are assessed and also due to deterministic models that emphasize other domains (Lätt et al., 2009; Morais et al., 2017).

To conclude, there are six general methods to evaluate drag, some more used to measure experimentally others numerically, these methods are valid and have specific characteristics (Study 1). The use of wearables to measure propulsion allows coaches to have more knowledge about strokes, kicks, FSA, among other variables (Study 2). Ending up alerting us to the relevance of using the C_D, where at the same speed it was mentioned that it allows us to have more knowledge about the hydrodynamic profile of swimmers. This should be the key parameter for measuring hydrodynamics in swimming (Study 3). According to the literature (Study 1) and the methods used by the authors to determine drag (resistive forces), it can be concluded that FSA, on one of the biomechanical subcategories of movement, played a fundamental role (Morais et al., 2020b; Taiar et al., 2005). Just as the technique appears to be a determining factor in reducing drag force and increasing propulsive force (Morais et al., 2024b; Toussaint et al., 2000). Drag tends to increase with speed and FSA, being greater in adults than in children due to body density factors and high levels of speed (Morais et al., 2020b; Gatta et al., 2015; González-Ravé et al., 2022). Furthermore, drag is greater in adults than in children and greater in men than in women in all age groups (Kolmogorov et al., 1997; Kolmogorov et al., 2021). However, C_D decreases as technical swimming efficiency increases (i.e., the best swimmers (the fastest or most efficient) are those with better drag and hydrodynamic swimming efficiency) (Cohen et al., 2018).

It is correct to say that studying drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming (Lopes et al., 2022; Morais et al., 2023). Although most authors agree with these findings, there is disagreement in some studies, especially when it is difficult to define competitive level and age (Gatta et al, 2016; Lopes et al., 2022; Vilas Boas et al., 2010). The divergence concerns three main aspects: (1) study deadline and improvement of methodologies; (2) discrimination of methodologies between factors observed in numerical vs experimental methods; (3) evidence that drag tends to be non-linear and depends on personal, technical and stylistic factors. Furthermore, due to the complexity of factors involving this modality, it was necessary to simplify and use practical methods (Study 2), through the use of wearables in swimming to facilitate and allow the measurement of propulsive forces, developing how wearables can be used to measure propulsive force in swimming with practical, real-time feedback. To this end, it is necessary to state that one of the practical contexts of swimming is the maximum speed acquired in a race, so this factor must be considered (Barbosa et al., 2013; Gatta et al., 2015), considering a set of kinematic and kinetic variables (Morais et al., 2020a). In this we noticed that swimming speed, propulsive force and other kinematic and kinetic variables did not change significantly ($p < 0.05$) between sections (only the intracyclic fluctuation of swimming speed decreased significantly, $p = 0.005$). On the other hand, the modeling maintained propulsive force, stroke length and C_{DA} as determinants of swimming speed. Therefore, considering that swimming speed was determined by the interaction of kinematic and kinetic variables, specifically propulsive force and C_{DA}, it is relevant to state that wearables prove to be extremely important in collecting data on the determinants of swimming (Lopes et al., 2023; Morais et al., 2022b). Furthermore, determining the resistive forces in crawl swimming at the same speed (i.e., 1.00, 1.05, 1.10 m/s, etc.) appears to yield some important results when comparing C_D and the difference between the use of the technical drag index (TDI) with drag (D_A and D_P) or with their respective C_D's (Havriluk, 2007; Kjendlie & Stallman, 2008; Morais et al., 2024c; Zamparo et al., 2009). As well as proficient swimmers showed higher C_{DA} than C_{DP}, but with strong agreement between them, probably due to FSA during active conditions. This states that C_D data appears to be a more absolute indicator of drag than TDI (Study 3). Knowing that TDI was calculated as a measure of swimming efficiency and FSA obtained in active conditions. Active FSA was 20.73 ± 5.56% greater than passive FSA (large effect size), propulsion was 58.29 ± 69.61% greater than drag and C_{DA} was 24.60 ± 46.55% greater than C_{DP} (moderate effect size). Another interesting value is that TDI was significantly lower, but with a small effect size when measured with C_D values compared to drag. TDI_D vs TDI_{CD} revealed strong agreement (>80% of plots were within the IC95).

Based on the results of the study and the importance of measuring propulsion in swimming, C_{DA} emerges as a standard variable to characterize the hydrodynamic profile of swimmers. The use of pressure sensors combined with IMU's allowed not only the assessment of propulsion, but also the detailed analysis of the hand trajectory in the three planes, providing valuable insights into angles of attack and other important biomechanical aspects. By observing that there were no significant differences in C_{DA} between different sections of the pool, it is suggested that swimmers can consistently maintain their hydrodynamic profile throughout different phases of a training session or competition. This highlights the importance of holistic training that addresses not only swimming technique, but also maintaining hydrodynamic efficiency throughout different conditions and phases of aquatic activity. For coaches and athletes, these findings have significant practical implications. By understanding the importance of C_{DA} and its relationship to swimming efficiency, they can direct their training efforts to improve not only swimming strength and technique, but also minimizing drag and maximizing propulsion. This may involve optimizing body posture, improving limb coordination, and adjusting hand entry and exit techniques in the water. Furthermore, awareness of the importance of hydrodynamic profile consistency across different swimming conditions can help athletes develop more effective training strategies and achieve improved performance in the pool. Based on the practical implications of the study on swimmers' hydrodynamic profile, coaches can implement several strategies in their training programs to improve their athletes' hydrodynamic efficiency: (1) coaches can use underwater videos and biomechanical analysis tools to examine closely monitor the swimming technique of its athletes, identifying areas of excessive drag and opportunities for optimization; (2) Instructing swimmers to maintain proper body posture can help reduce drag and improve efficiency. This includes keeping the body line as straight as possible and avoiding breaking the hydrodynamic position while swimming; (3) Smooth hand entry into the water and efficient exit from the stroke cycle are crucial to minimizing drag. Coaches can incorporate specific drills to improve these skills, such as hand entry drills and stroke recovery drills; (4) developing swimmers' strength and flexibility can help them maintain an ideal body position in the water, reducing drag and improving propulsion; (5) as the hydrodynamic profile can be affected by fatigue, coaches can integrate training sessions that aim to improve swimmers' ability to maintain efficient technique even when tired; (6) Providing regular feedback to swimmers on their swimming technique and hydrodynamic profile is essential to ensure constant improvements. The use of technology, such as video analytics and pressure sensors, can assist in this process.

Chapter 5. Overall Conclusions

As main conclusions, it can be stated that although there is no gold standard method for measuring forces in water, whether resistive or propulsive, we acknowledge that there are several methods for measuring these forces. Nonetheless, such values derived from these results should be understood. As far as resistive forces (drag) are concerned, it can be stated that there are numerical and experimental methods that can be used, depending on the type of study or evaluation that is intended to be carried out. When it comes to propulsive forces, pressure sensors are an easy-to-use and reliable method to control and optimize training in real time. Despite this, for any method, the hypothesis that there is a correction factor applied when different methods are considered must be considered. Based on the complexity of studying the phenomena that involve swimming, we can understand that when studying drag, this phenomenon must be continued and framed to improve swimming performance. Otherwise, the use of wearables is a great complement to swimming. These allow you to measure driving force and present it to coaches and swimmers with immediate feedback. The swimmers did not significantly change their swimming speed, as well as their propulsive force and other kinematic and kinetic variables measured. Likewise, coaches and swimmers must be aware of the importance of balance both in generating propulsive forces and in reducing resistive forces. Finally, it is stated that the swimmers presented a C_{DA} greater than the C_{DP}, but with strong agreement between them, due to the variation in the FSA during active conditions. And it seems that the TDI, as an indicator of swimming efficiency, can be overestimated when using absolute drag values instead of their respective C_{DA}. In other words, it is necessary to start looking at the variables that involve swimming with a more comprehensive importance than has been done, because each variable will probably have its importance in the results that arise in it and therefore each one should not be ignored. This simply proves that we often consider that a certain variable is more important than another for several reasons, but something that is not evident, as this example proves.

Chapter 6. Suggestions for future investigations

The main outputs of this thesis provide the possibility of new studies about this topic that want to focus on practical evidence. As well as, presenting that the biomechanical characteristics that involve swimming should not be discarded or studied separately, but rather framed in a logical way (justifying this separation when applicable). Where most biomechanical characteristics are complementary and therefore may no longer make sense when studied separately. Therefore, the following are suggestions for future research:

1. Carry out longitudinal studies capable of collecting more complete information, enabling a way to obtain data on resistive force and propulsive force in addition to other possible variables described throughout this thesis. Both forces mentioned are mutually influenced so it is not logical to separate them as if it were possible to ignore one or the other;
2. Monitor the force in the water (propulsion) and the force in the dry (training on dry land) to be able to study the relationship between them. This falls within the scope of sports seasons, and may cover more variables external to the exclusive performance of swimming (aquatic training actions), considering other specific training regimes/training programs (for example, training on dry land, elastic bands, free weights and water training), understand the transfer between strength on dry land and strength and performance in the water. In order to understand its effect on forces in the water in relation to other variables that are functional standards for swimming performance, especially at high speeds. This isn't possible without ignoring all the variables that involve a functional movement pattern for aquatic performance;
3. The closer to best performances the better, thus if possible, it would be important to carry out identical studies on elite and master swimmers and understand the variability of force in the water (propulsion) over a given time;
4. No less important, in addition to the elite, a sample that takes into account Paralympic athletes;

Chapter 7. References

Chapter 1

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Chapter 2 – Study 1

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Appendix I

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Appendix II

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Appendix I

Numerical and experimental methods used to evaluate active drag parameters in swimming

Abstract

In swimming, it is necessary to understand and identify the main factors that are important to reduce active drag and, consequently, improve the performance of swimmers (Kolmogorov & Duplishcheva, 1992). However, there is no up-to-date review in the literature clarifying this topic. Through of 75 studies related to active drag in swimming and the methodologies applied to study them were analyzed and kept for synthesis. The included studies showed a high-quality score by the Delphi scale (mean score was 5.85±0.38). In both methods (numerical and experimental), it can be concluded that the frontal surface area plays a fundamental role (Morais et al., 2020). Additionally, the technique seems to be a determining factor in reducing the drag force and increasing the propulsive force. Drag tends to increase with speed and frontal surface area, being greater in adults than in children due to body density factors and high levels of speed (Barbosa et al., 2019). However, the coefficient of drag decreases as the technical efficiency of swimming increases (i.e., the best swimmers (the fastest or most efficient) are those with the best drag and swimming hydrodynamics efficiency) (Kolmogorov, Vorontsov & Vilas-Boas, 2021). The study of drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming. Although most agree with these findings, there is disagreement in some studies, especially when it is difficult to define competitive level and age. The disagreement concerns three main aspects: (1) period of the studies and improvement of methodologies; (2) discrimination of methodologies between factors observed in numerical vs experimental methods; (3) evidence that drag tends to be non-linear and depends on personal, technical, and stylistic factors (Sacilotto, Ball & Mason, 2014). Based on the complexity of active drag, the study of this phenomenon must continue to improve swimming performance.

Lopes, T. J., Pinto, M. P., Marinho, D. A., & Morais, J. E. (2023). Numerical and experimental methods used to evaluate active drag parameters in swimming. *Seminário Desporto e Ciência 2023*. University of Madeira, Portugal.

Appendix II

Numerical methods used to assess active drag in swimming over the years

Abstract

Is necessary identify and understand and identify the main factors that are important to reduce active drag and, consequently, improve the swimmers' performance. However, there is no up-to-date review in the literature clarifying this topic. Thus, a methodological review was carried out to review what is known about active drag in swimming through numerical methods. The objective was to determine and identify the most relevant studies for this review. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was used. Seven studies related to active drag were analysed (table 1). The included studies (figure 1) showed a high-quality score by the Delphi scale (mean score was 5.57±0.51). Most studies were focused on the front crawl stroke for submaximal speeds (Cohen, Cleary & Mason, 2012; Cohen et al., 2018; Yuan et al., 2019). Another study analysed the effects of buoyancy during swimming and the drafting as a performance parameter for competition (Cohen et al., 2014). The study by Keys and Lyttle (2007) demonstrated that it is beneficial to use the underwater flutter kick over the large/slow kick or the small/fast kick using the CFD method. Other studies (Cohen et al., 2018; Cohen et al., 2020) suggested that vortices generated in the water during swimming can be used to increase propulsion through vortex recapture. Furthermore, the coefficient of variation is higher for strikes with synchronised movement of the limbs. The coefficient of variation, and consequently the active drag, changes depending on the phase of movement or swimming, being different between kicks and strokes (Cohen et al., 2015). There are significantly fewer numerical studies than experimental ones. This situation can be due to active drag, as a dynamical phenomenon, being too complex to be numerically studied. The main results of the analysed studies indicated that the frontal surface area and all the surrounding technical components play a fundamental role. Swimming technique remains a determining factor in reducing drag force and increasing propulsive force. Active drag can be studied through numerical and experimental methods. The study of drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming. Numerical studies are a powerful add-on to experimental studies due to the gold-standard models used.

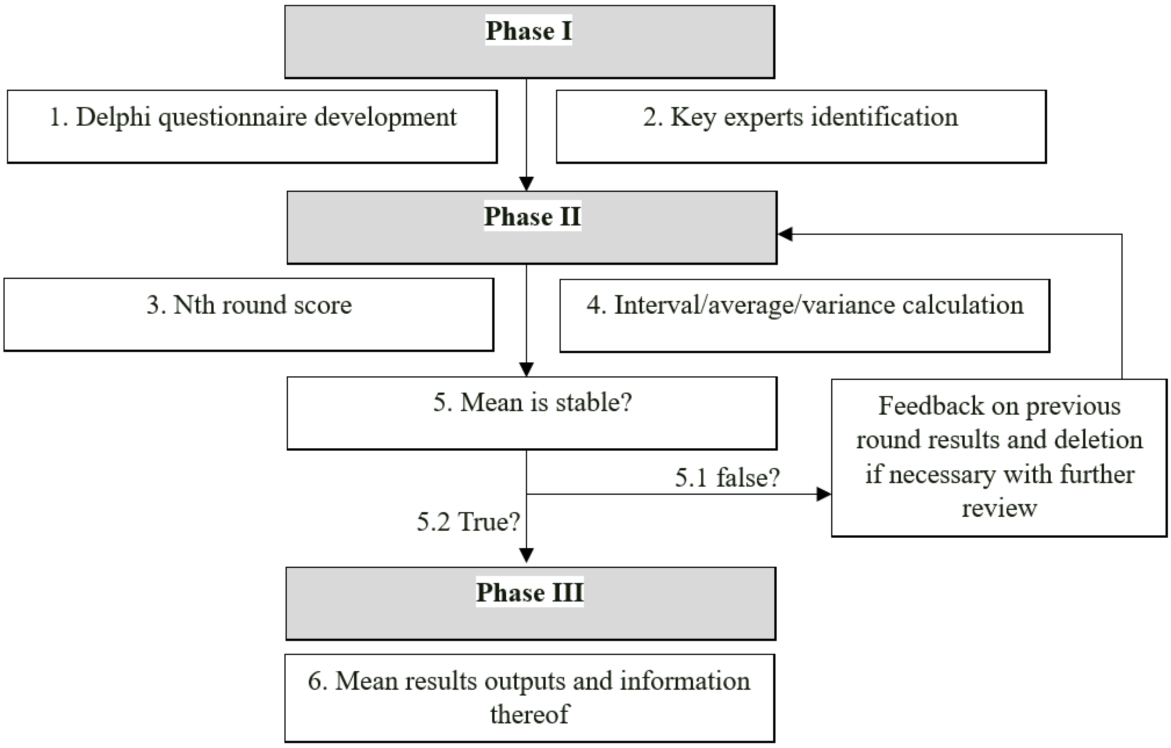

Figure 1. Flowchart development for the Delphi questionnaire applied for the study

Table 1. Summary of the objective, sample demographics, and main results of the studies related with D_A for numerical methods.

Study (year)	Objective	Subjects (age and competitive level)	Results	Delphi score Mean±1SD
Cohen et al., (2012)	Determine the relative importance of the extension kick (often called downbeat) compared to the flexion kick (often called upbeat) in dolphin kick swimming	Smoothed Particle Hydrodynamics (SPH). Laser scans of athletes are used to provide realistic swimmer geometries in a single anatomical pose. These are rigged and animated to closely match side-on video footage	Swimmer strength depends on kick frequency and is insensitive to ankle flexibility. The maximal drag force occurs in the direction of the current, corresponding to the periods before the inversions of strokes, and swimmers must pay attention to the rapid inversions of direction	5.0±0.0
Cohen et al., (2014)	Determine the pitching effects of buoyancy during all competitive swimming strokes (front crawl, backstroke, butterfly, and breaststroke)	Laser body scans of national-level athletes and synchronized multiangle swimming footage were used in a novel markerless motion capture process to produce three-dimensional biomechanical models of the swimming athletes	Variation in buoyancy torque is much larger during breaststroke and butterfly than during front crawl and backstroke; pitching swimmer moment of inertia varies much more for butterfly and breaststroke than for front crawl and backstroke; that buoyancy torque and pitching swimmer moment of inertia are anticorrelated during butterfly and breaststroke	5.0±00
Cohen et al., (2015)	A combination of kinematic data and SPH-based flow modeling was used to explore the degree to which the instantaneous impulse generated by the arms is controlled by the trajectories of the hands, their orientation and speeds during the front crawl stroke.	SPH fluid model is used to analyze the thrust and drag generation of a front crawl swimmer. The swimmer model was generated using a three-dimensional laser body scan of the athlete and digitization of multi-angle video footage (CFD)	Two large distinct peaks in liquid thrust coincide with underwater strokes. The movement of the hands generates vortex structures that travel along the body (there is the production of lift and drag)	6.0±0.0
Cohen et al., (2018)	Investigate how the streamwise speed and net streamwise forces of the swimmer vary throughout the phases of the stroke. The dependence of the relative thrust from the arms compared to the legs on the stroke rate was also investigated	A dynamic biomechanical model of a female national-level swimmer was generated from a three-dimensional laser body scan of the athlete and multi-angle videos of sub-maximal swimming trials (CFD)	The Froude number varies from 0.40 to 0.31, meaning that the swimmer swims close to Fr=0.42 (hull speed), consequently the drag of waves on the surface is significant	6.0±0.0
Cohen et al., (2020)	The asymmetrical front crawl swimming performance of a male elite level swimmer who breathed every second arm stroke (unilaterally) was investigated	A laser body scan and multi-angle video footage of the athlete were used to generate a swimming biomechanical model (one male elite level)	The natural asymmetrical performance with the swimming movement acquired through the frontal area results in a greater D_A (swimmer's technique) are the main findings. These will help improve athletes' performance and coaches' decision making	6.0±0.0
Keys & Lyttle, (2007)	Sought to discriminate between the D_A and propulsive forces generated in underwater dolphin and flutter kicking using the CFD technology	A 3D image of an elite swimmer was animated using results from a kinematic analysis of the swimmer performing two different patterns of underwater dolphin kick (large/slow kicks versus small/fast kicks) and the underwater flutter kick	Advantage in using the swim kick in the underwater flutter kick over the small/fast or large/slow kick at 2.18 m/s There are benefits in prescribing techniques through the use of CFD models	6.0±0.0
Yuan et al., (2019)	Find the mechanism of the hydrodynamic interaction between human swimmers and to quantify this interactive effect by using a steady potential flow solver	Only interested in the wave drag component. No attempt is made here to analyze the other drag components due to the viscosity of the fluid. One passive swimmer; three swimmers in competitive swimming; and another observations	Showed that the hydrodynamic interaction made a significant contribution to the drafter's wave drag. By following a leading swimmer, a drafter at wave-riding positions could save up to 63% of their wave drag at speed of 2.0 m/s and lateral separation of 2.0 m/s. When a drafter is following two side-by-side leaders, the drag reduction could even be doubled	5.0±00

D_A – active drag; CFD – computational fluid dynamics; SPH – coupled biomechanical-smoothed particle hydrodynamics; F_r – froude number; C_D – coefficient of drag; SD – one standard deviation

Lopes, T. J., Morais, J. E., Pinto, M. P., & Marinho, D. A. (2023). Numerical methods used to assess active drag in swimming over the years. *Cidesd International Congress 2023*. University of Trás-os-Montes and Alto Douro, Portugal.