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Techniques and considerations for monitoring swimmers' passive drag

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ABSTRACT

Drag is the resistant force that opposes a swimmer displacing through water and significantly affects swimming performance. Drag experienced during active swimming is called active drag (D_a), and its direct determination is still controversial. By contrast, drag experienced while gliding in a stable streamlined body position is defined as passive drag (D_p), and its assessment is widely agreed upon. D_p reduction preserves the high velocity gained with the push-off from the starting block or wall after starting and turning or improves the gliding phase of the breaststroke cycle. Hence, this paper reviewed studies on swimming that measured D_p under different conditions of gliding. In the present research, accurate descriptions of the main methods used to directly or indirectly determine D_p are provided and the main advantages, limitations and critical features of each method are discussed. Since D_p differs in methods but not in reported values and is consistent regardless of the measuring method, the information provided in this paper might allow coaches and practitioners to identify the most suitable method for assessing and determining the drag of their swimmers.

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Introduction

Swimming velocity depends on the relationship between the propulsive forces applied to displace water and resistant forces working against a body moving through water. The most efficient way to increase velocity is to reduce these resistant forces since this reduction does not require increases of energy expenditure or an energy cost (Barbosa et al., 2010). Hence, measuring and monitoring the resistive forces during swimmers' displacement through water are key factors in finding the most effective body position assumed to reduce the forces opposing propulsive actions.

The force that resists movement through water is called drag (D), which has been defined as "the force on an object moving in a fluid due to the rate of change in momentum of the fluid influenced by the object moving through the fluid" (Vogel, 1994). During swimming, a quadratic drag-speed relationship occurs (Toussaint et al., 1988). According to the literature, even if the water flow all around a swimmer is not always steady and changes at varying speeds, the velocity exponent is assumed to be very close to 2.0 (Martin, 1989).

The drag acting on a swimmer moving through water has three main components: i) friction drag, which his linked to the boundary layer when water passes over the swimmer's body; ii) pressure drag, which depends on the shape of the swimmer's body and its cross-sectional surface area in particular; and iii) wave drag, which is related to wave formation around the body while swimming at or near the water surface (Toussaint, Hollander, Van den Berg, & Vorontsov, 2000). Together, these components define the swimmer's total drag, as well as the drag coefficient. Despite the controversial issues concerning their relative contribution to the swimming velocity, it is generally accepted that friction drag has a linear relationship with velocity, that pressure drag has the most relevance at low and mid swimming velocities and has a square relationship and that wave drag exerts its main contribution at high velocities through a cubic relationship (Lyttle, Blanksby, Elliott, & Lloyd, 1999).

The resistance opposing a swimmer displacing water with a stable body has been defined as passive drag (D_p) (Clarys, 1985). Therefore, D_p is measured in the streamline position, which is assumed to be the best hydrodynamic position to reduce the aforementioned drag components during gliding. In the streamlined position, the body is aligned and fully extended; the arms are straight and high, with one hand over the other; the head is between the arms and facing down; the legs are straight and joined; the feet are extended at the ankle and plantarflexed; and no movements of limbs or body are exerted to propel the body.

The streamlined position is taken by the swimmer during the glide phase after performing a start and/or turn. This position is held as long as possible to optimize the velocity gained by the push off from the starting block or turning wall. The gliding phase has been measured to correspond to 10 to 25% of the race, as a function of the distance of the event or of the pool length (Guimaraes & Hay, 1985; Lyttle, Blanksby, Elliott, & Lloyd, 2000; Marinho et al., 2009). Finally, the glide phase is also an important component of the breaststroke stroke cycle for many swimmers (Naemi & Sanders, 2008). Hence, reducing D_p can lead to a more efficient glide phase and to a corresponding decrease in the race time. In fact, the body shape as well as body size seem to have a great effect on the streamline gliding of swimmers (Naemi & Sanders, 2008),

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and swimmers' performance is highly related to the glide phases (Cossor & Mason, 2001).

Havriluk (2007) analysed several methods used in the literature to determine D_p according to methodological differences, such as water body (pool, flume, tank), stabilization systems (tow line or carriage) and theoretical methods (added or subtracted drag), and found that they measured consistent values of D_p.

The resistance experienced by a swimmer while moving through water is defined as active drag (D_a). During the swimming phase, the body is never held in a stable prone position since the limbs move to generate propulsion. These actions are supposed to affect D_a (Toussaint, Roos, & Kolmogorov, 2004). Several and quite dissimilar methods have been proposed to measure D_a, resulting in several opinions and scientific arguments that have not yet been solved (Zamparo, Capelli, & Pendergast, 2011). Some authors have measured the value of D_a as two or more times higher than that of D_p (Takagi, Shimizu, & Kodan, 1999; van der Vaart et al., 1987), and other authors' D_a values corresponded to approximately 1.5 D_p (Di Prampero, Pendergast, Wilson, & Rennie, 1974; Gatta, Cortesi, Fantozzi, & Zamparo, 2015), while others found D_a to be comparable or lower than D_p (Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Toussaint et al., 1988). Altogether, these concerns imply that D_a measurements are currently more questionable in regard to methods and results compared to D_p measurements, which appear to be less controversial for assessing the drag values (Havriluk, 2007; Zamparo et al., 2011).

The aim of this paper was to examine the methods used in the literature to measure swimmers' D_p. To guide this review, the following research questions were examined:

1) What are the methods used in swimming research to measure D_p?
2) What were the main purposes and topics examined by the literature?
3) What equipment is required to measure D_p, and how are the procedures carried out?
4) What are the main advantages and limitations of each procedure?

The answers to these research questions may help coaches and practitioners to identify the most appropriate method to measure the passive drag of their swimmers as well as to improve their performance evaluation and training.

Methods

Literature search methodology

PubMed, Web of Science and Scopus were searched to identify studies that analysed swimmer's passive drag. The following keywords/combinations were used in the searches: 'passive drag' OR "drag" AND "swimming", appearing in the title, abstract and keyword fields of the text. The search included all studies published before March 2018.

As an initial search strategy, papers monitoring swimmer's passive drag were restricted to i) articles (review papers, books and conference proceedings were excluded), ii) studies written in English, iii) sport sciences as the primary research area, and iv) only including human participants.

As a second advanced search criterion, only research that involved humans or models of able competitive swimmers were selected. Studies involving triathletes, pentathletes and water polo players were excluded from the review. Duplicates acquired from multiple databases were also excluded. These search criteria were deemed appropriate and consistent with the purpose of the study to consider the specific use of passive drag for evaluation of swimming drag in subjects with good technical swimming skills.

Quality assessment

For the quality assessment, questions derived from Caldas, Mundt, Potthast, Buarque de Lima Neto, and Markert (2017) were used to assess the rigorousness, credibility, and relevance of the studies that met the inclusion criteria. This checklist was chosen because we did not find validated quality assessment tools suitable for this type of intervention (i.e., comparison of measurement methods). Items for the methodological assessment included 10 questions related to definition of the aims (1); description of the context (2); definition of the methods (3); experimental design (4); project data sets (5); accuracy measures or reports (6); comparisons with other methods (7); findings report (8); limitations explication (9); and impact of the study (10). Each question has only three answers (i.e., "Yes", "Partly" or "No"), which are respectively rated as follows: "1", "0.5", and "0". Quality results were computed by summing the scores of the answers. Two independent reviewers examined each paper and answered all questions. Agreement between the two independent reviewers was checked by calculating Cohen's Kappa.

Results

Study inclusion

A total of 1535 studies were identified from all of the databases searched by the selected keywords (471, 961 and 103 papers from PubMed, Web of Science and Scopus, respectively).

Studies duplicated from multiple databases were excluded after the initial search strategy, and the first restriction according to paper type, language, research area and participants limited the results to 371 citations (157, 168 and 46 papers from PubMed, Web of Science and Scopus, respectively).

Application of the second advanced selection criteria resulted in a final total of 40 papers that were used for our analysis. One paper was included from outside the search (International Sportmed Journal).

The 41 papers were categorized according to the method used by the authors to measure D_p: towing and flume as direct measurement methods or gliding decay and computational fluid dynamics (CFD) as indirect measurement methods. The description of the measurement procedure, findings of the measured parameters, comparisons with the literature, and the details and limitations have been reported for each method.

Quality of studies

The quality assessment scores of each study are reported in Table 1. The average agreement between the two independent reviewers, as measured by Cohen's Kappa, was .74, which is regarded as good agreement. Ratings of the selected papers ranged from medium to high, highlighting their quality and pertinence for examining the D_p measurement methods, which was the aim of the present study.

With the exceptions of Clarys (1985) and Vennell, Pease, and Wilson (2006), all studies had clearly defined aims. The context was satisfactorily described by all papers, but ten studies did not define the methods precisely (Barbosa et al., 2013; Barbosa, Ramos, Silva, & Marinho, 2018; Costa et al., 2015; Kjendlie & Stallman, 2008; Li & Zhan, 2015; Marinho, Barbosa, Rouboa, & Silva, 2011; Maruyama & Yanai, 2015; Narita, Nakashima, & Takagi, 2017; Novais et al., 2012; Zhan, Li, Chen, Li, & Wai, 2015). Seventeen of the 41 selected studies scored Partly or No in the question about the use of an appropriate and justifiable experimental design (Barbosa et al., 2013, Barbosa, Morais, Forte, et al., 2015; Benjanuvatra, Blanksby, & Elliott, 2001; Benjanuvatra, Dawson, Blanksby, & Elliott, 2002; Formosa, Mason, & Burkett, 2011; Gatta, Cortesi, & Di Michele, 2012; Gatta, Zamparo, & Cortesi, 2013; Marinho et al., 2011, 2009; Morais et al., 2013; Narita et al., 2017; Roberts, Kamel, Hedrick, McLean, & Sharp, 2003; Vennell et al., 2006; von Loebbecke, Mittal, Mark, & Hahn, 2009; Zaïdi, Fohanno, Taïar, & Polidori, 2010; Zaïdi, Taïar, Fohanno, & Polidori, 2008; Zhan et al., 2015).

Table 1. Synopsis of the selected 40 articles that measured D_p. The articles are ordered according to the chronological year of publication, and the methods used to determine D_p are indicated as: (+) = main measurement; (-) = secondary measurement. The quality assessment score is reported in the QA column.

			Measurement method			
References	Year	QA	Towing	Flume	Gliding Decay	CFD
Clarys	1985	7.5	+			
Chatard, Bourgoin, and Lacour	1990	6.0	+			
Chatard, Lavoie, et al.	1990	6.5	+			
Chatard et al.	1995	7.5	+			
Benjanuvatra et al.	2001	7.0	+			
Benjanuvatra et al.	2002	7.5	+			
Chatard and Wilson	2003	6.5		+		
Roberts et al.	2003	6.5		+		
Mollendorf et al.	2004	9.0	+		-	
Vennell et al.	2006	7.5		+		
Bixler et al.	2007	9.5		-		+
Chatard and Wilson	2008	7.0		+		
Kjendlie and Stallman	2008	7.0			+	
Silva et al.	2008	8.5				+
Zaidi et al.	2008	8.0				+
Marinho et al.	2009	7.0				+
von Loebbecke et al.	2009	8.0				+
Zamparo et al.	2009	9.0	+			
Vilas-Boas et al.	2010	8.0			+	
Zaidi et al.	2010	7.5				+
Formosa et al.	2011	7.0	+			
Marinho et al.	2011	6.5				+
Gatta et al.	2012	7.0	+			
Novais et al.	2012	7.0				+
Barbosa et al.	2013	7.0			+	
Formosa et al.	2013	8.0	+			
Gatta et al.	2013	7.0	+			
Morais et al.	2013	6.5			+	
Cortesi et al.	2014	8.0	+			
Pacholak et al.	2014	7.5				+
Barbosa, Morais, Forte, et al.	2015	7.0			+	
Barbosa, Morais, Marques, et al.	2015	8.0			+	
Cortesi and Gatta	2015	9.0	+			
Costa et al.	2015	8.0			-	+
Li and Zhan	2015	6.0				+
Maruyama and Yanai	2015	5.5	+			
Tor et al.	2015	8.0	+			
Zhan et al.	2015	5.0				+
Gatta et al.	2016	9.5	+			
Narita et al.	2017	5.5		+		
Barbosa et al.	2018	6.5				+

For the question on the use of sufficient project data sets, we decided to consider the number of measurement conditions used (i.e., 1, 2 or ≥ 3 D_p measurement velocities), as reported in Tables 2–5. Twelve studies assessed D_p in one condition (Barbosa et al., 2013, 2015, 2015; Chatard, Bourgoin, & Lacour, 1990; Chatard, Lavoie, Bourgoin, & Lacour, 1990; Chatard & Wilson, 2003; Formosa et al., 2011; Formosa, Sayers, & Burkett, 2013; Kjendlie & Stallman, 2008; Narita et al., 2017; Pacholak, Hochstein, Rudert, & Brucker, 2014; von Loebbecke et al., 2009).

The accuracy was limited or not fully rated in seven of the selected papers (Barbosa, Morais, Forte, et al., 2015, Barbosa at al., 2018; Gatta et al., 2012; Morais et al., 2013; Narita et al., 2017; Pacholak et al., 2014; Zhan et al., 2015). Most of the studies did not use a comparative method to validate the results, except for three papers (Bixler, Pease, & Fairhurst, 2007; Costa et al., 2015; Mollendorf, Termin, Oppenheim, & Pendergast, 2004).

All of the studies clearly or satisfactorily supported their findings by reporting results, but only thirteen papers explicitly explored the limitations of their studies (Barbosa et al., 2013, Barbosa, Morais, Forte, et al., 2015; Bixler et al., 2007; Clarys, 1985; Cortesi, Fantozzi, Di Michele, Zamparo, & Gatta, 2014; Formosa et al., 2013; Gatta et al., 2012; Gatta, Cortesi, & Zamparo, 2016; Kjendlie & Stallman, 2008; Morais et al., 2013; Novais et al., 2012; Silva et al., 2008; Zamparo, Gatta, Pendergast, & Capelli, 2009).

Finally, to answer the question about the added value of the studies to the academic community, we decided to refer to the ratio of number of Scopus citations to the year of publication, which was delineated into quartiles. Three studies obtained a low score, possibly due to the recentness of publication or because they were published in journals without an impact factor (Barbosa et al., 2018; Maruyama & Yanai, 2015; Morais et al., 2013).

Literature overview

Synopses of all of the papers included in this review are reported in Table 1.

D_p is a contemporary issue in swimming: most of the papers we considered are recent and were published after 2008. A majority of the authors used the towing method to assess D_p, followed by the CFD method.

Towing method

The towing method is the most commonly used procedure in the literature to assess D_p, possibly because of its validity and ease of use. Indeed, the validity of the towing method has been widely demonstrated, and its reliability for the D_p measurement is very high (Cortesi & Gatta, 2015; Mollendorf et al., 2004).

Pioneers of this method started measuring the resistive forces against swimmers' displacement using a dynamometer while towing swimmers with rowing boats (Amar, 1920; Dubois-Reymond, 1905). Amar (1920) first defined the exponential relationship between the resistive forces and towing velocity as $D = k \cdot v^2$, where D is the drag value (N), k is a constant value, and v is the swimming velocity ($m \cdot s^{-1}$). Karpovich (1933) defined the k value in his experimental outcomes, measuring $D = 29 \cdot v^2$. At the most commonly used velocities at which competitive swimmers are measured (1.6 to 1.8 $m \cdot s^{-1}$), the D_p values range between 55 N and 90 N, depending on age, gender and anthropometric features. In addition, towing methods measure different D_p values as a function of towing depth or the swimmer's body position: when the water depth increases, a large decrease in total drag is reported (from 19% to 23%), regardless of speed (Tor, Pease, & Ball, 2015).

The testing procedure of the towing method requires an automated towing machine (usually an electromechanical motor) placed at the end wall of the pool that has a power that exceeds the expected swimmers' D_p values at the planned towing velocities (the power usually ranges between 0 and 400 W). Swimmers are tied to a towing cable that must be inextensible to avoid any absorption of force. When the testing protocol requires a measurement in the streamline position, the swimmers hold the cable by a handle or lace, whereas in the measurement where the arms have to be aligned along the body, the cable is attached under the armpits or at a hip-belt. Common procedures perform the measurements 3 to 5 times at each target velocity. Otherwise, incremental trials are repeated, usually from 1.0 to 2.4 $m \cdot s^{-1}$, with the appropriate number of steps to obtain the force/velocity curve function.

As suggested by Caspersen, Berthelsen, Eik, Pakozdi, and Kjendlie (2010), at the beginning of the testing protocol, a wide increment of D_p values is measured because of the added mass acting on the swimmer during the acceleration phase. As the swimmer is towed at a stationary velocity, that is, after 8 to 10 m, D_p stabilizes and, at that moment, the resistive forces can be measured.

A synopsis of the papers that used a towing method to measure D_p is provided in Table 2, showing all of the details of the participants' demographics, of the testing procedures and of the measured values.

The towing method has as a great advantage for directly measuring D_p. Furthermore, the strap attaching the swimmer to the towing apparatus does not disturb the glide and allows the swimmer to assume and hold the actual streamlined position, the towing method reproduces the gliding condition that the swimmers experience after starts and turns, as well as during the breaststroke glide phase. Finally, measurement devices can be easily set to tow at different speeds. Therefore, the effective speeds of displacement of swimmers in the different phases of a race can be reproduced, as well as gliding at slow, high or hyper-velocity, allowing for a direct assessment of D_p over a wide spectrum of conditions that can be related to the swimmers' skills.

Towing is affected by a small constraint during the measurement due to the limited ability of dynamometers to discriminate among small changes of the drag values. Occasionally, when perceiving some instability because of waves or water flow, swimmers make small corrections to manage and hold the streamlined position (e.g., the depth of towing, head position, orientation of the hands). Even if this is often negligible because of the small magnitude or because of the swimmers' skills and testing protocols allowing the glide to be monitored during measurements, these corrections affect the accuracy of the towing procedure.

Flume method

The flume method measures D_p in swimming flumes, a small swimming pool that acts such as an aquatic treadmill, with the swimmer swimming in channels of precisely controlled flowing water with the swimmer steady with respect to the environment.

The procedure that the swimmers follow is similar to the previously described towing method: the swimmer has to assume the best hydrodynamic position and is tied to a cable. Conversely, the procedure differs in regard to the measuring equipment, as the swimmer does not displace water and is connected to a fixed load cell by a handle or lace. The flow speed of water is controlled by flow sensors and can be precisely modified to vary the relative swimmer/water velocity according to the requirements of the testing procedure. D_p acting on the swimmer is measured by dynamometers, similar to wind tunnels systems, in which subjects or objects are placed and sensors measure the pressure distribution of the air flow around the model, as well as other aerodynamic-related characteristics.

A remarkable consistency between the measurements performed by the flume and by towing methods has been confirmed (Havriluk, 2005) and, as shown in Table 3, the D_p values are comparable: at a velocity of 2.0 $m \cdot s^{-1}$, the D_p values from a flume are approximately 110 N in relation to the swimmers' anthropometrics, which means they are very close to the D_p values measured by the towing method (Chatard & Wilson, 2008; Clarys, 1985; Cortesi et al., 2014; Vennell et al., 2006).

The main advantage of the flume method is that the conditions of the measurement can be standardized in the same way that a treadmill replicates a stable experimental setting while studying running. Therefore, a swimming flume can simulate several conditions to study D_p, such as open water events, which can be preserved and repeated for successive measurements and those that differ in time.

However, limitations are found in this procedure. The differences between swimming in a water flume and a swimming pool have been studied (Hay & Carmo, 1995; Wilson, Takagi, & Pease, 1998), and some factors have been observed that may interfere with the stroke actions, making the experimental phenomena while swimming in a flume different from those while actually swimming. In fact, the reduced distances between the walls of the flume equipment compared to the wide size of swimming pools and the features of the engines producing the water flow might interfere with the flow around the swimmer in a way that is different than during actual swimming. Therefore, the free-stream turbulence and wave that are created artificially by the flume current have to be carefully controlled (Chatard & Wilson, 2003).

Gliding decay velocity method

Different from the two previously described methods, the gliding decay velocity method aims to assess D_p from the

Table 2. List of the articles that used the *Towing method* to measure D_p, organized by author and containing all of the details related to the participants, protocol of measurement, D_p values, drag coefficient (Cd) or K coefficient (K), and purpose of the study.

References	Participants description (Sample size, Mean ± SD) (n, years)	Swimmer's position	Depth (m)	Swimmer's velocity ($m \cdot s^{-1}$)	D_p (N)	K* or Cd** coefficient	Purpose of study
Benjanuvatra et al. (2001)	Young swimmers (n = 6 M; n = 6 F, 9 ± 1) (n = 6 M; n = 6 F, 11 ± 1) (n = 6 M; n = 6 F, 13 ± 1)	Prone with arms extended over the head	0	 1.3 1.6 1.9 2.2 2.5	*9 y; 11 y; 13 y* 26; 28; 29 41; 43; 46 57; 64; 70 73; 85; 95 94; 106; 119	Not described	Effects of morphology on passive drag
Benjanuvatra et al. (2002)	National level swimmers (n = 5 M; n = 4 F)	Prone with arms extended over the head	0; 0.4	 1.6 2.2 2.8	*0 m; 0.4 m* 58.2; 50.7 118.1; 76.1 171.6; 122.7	Not described	Comparison of drag between swimsuits
Chatard et al. (1990)	Competitive swimmers (n = 90 M, 16.2 ± 2.8) (n = 69 F, 14.6 ± 1.0) by velocity level (*A, B, C*)	Prone with arms extended over the head	0	 1.4 1.4 1.4	*M; F* (*A*) 46; 48 (*B*) 51; 48 (*C*) 53; 48	Not described	Anthropometric and joint laxity variations on passive drag
Chatard et al. (1990)	Competitive swimmers (n = 48 M, 16.1 ± 3.5) (n = 36 F, 14.8 ± 2.0)	Prone with arms extended over the head	0	 1.4	*M; F* 50; 48	Not described	Passive drag contribution to prediction the 400-m performance
Chatard, Senegas, Selles, Dreanot, and Geyssant (1995)	Swimmers (n = 8 M)	Prone with arms extended over the head	0	1.0 1.2 1.4 1.6 1.8	25 38 50 60 70	Not described	Swimsuit effects on performance
Clarys (1985)	Not described	Prone with arms extended over the head	0; 0.6	1.6 1.7 1.8 1.9 2.0	74 80 90 103 116 *(visual inspection)*	Not described	Links between hydrodynamics and electromyographical aspects of swimming
Cortesi and Gatta (2015)	Regional level swimmers (n = 10 M, 21 ± 2)	Prone with arms extended over the head (*A*); Prone with arms along the body (*B*)	0	 1.5 1.7 1.9	*A; B* 95; 77 121; 98 154; 121	Not described	Effect of the head position on passive drag
Cortesi et al. (2014)	Regional level swimmers (n = 14 M, 24 ± 4)	Prone with arms extended over the head	0	1.6 1.8 2.0	72 90 120	28.6*	Full-body swimsuits effect on the swimmer's body alignment
Formosa et al. (2011)	Elite swimmers (n = 8 M, 22.1 ± 1.7)	Prone with arms extended over the head	0	1.92	80	Not described	Quantifying the force–time profile of elite swimmers
Formosa et al. (2013)	Elite swimmers (n = 10 M, 21.2 ± 2.9) (n = 9 F, 18.8 ± 3.1)	Supine with arms extended over the head	0	1.63	57	Not described	Gender differences in passive drag
Gatta et al. (2012)	High-level competitive swimmers (n = 18 M, 21.3 ± 3.6)	Prone with arms extended over the head	0	1.0 1.2 1.4 1.6 1.8 2.0	25 38 52 66 86 113	Not described	Power production by flutter-kick at different velocities
Gatta et al. (2013)	Highly trained swimmers (n = 16 M, 26.5 ± 8.6)	Prone with arms extended over the head	0	1.5 1.7 1.9	56 74 99 *(visual inspection)*	Not described	Effects on passive drag of wearing different models of swim caps

(*Continued*)

Table 2. (Continued).

References	Participants description (Sample size, Mean ± SD) (n, years)	Swimmer's position	Depth (m)	Swimmer's velocity ($m \cdot s^{-1}$)	D_p (N)	K* or Cd** coefficient	Purpose of study
Gatta et al. (2016)	Elite swimmers (n = 10 M, 23.0 ± 3.4)	Prone with arms extended over the head	0	1.0 1.3 1.6 1.9 2.2	32 45 59 82 120	Not described	Estimating of the power generated by thrust and drag forces
Maruyama and Yanai (2015)	Physically active college swimmers (n = 11 M, 24.0 ± 2.5)	Prone with arms extended over the head	Between 0.4 and 0.9	1.13 1.25 1.52 1.95	34.3 39.2 58.9 98.1	30*	Effect of altering breathing manoeuvre on the passive drag
Mollendorf et al. (2004)	University Division I swimmers (n = 7 M, 20.2 ± 0.5)	Prone with arms extended over the head	0	2.2	86.2	Not described	Differences in passive drag induced by swimsuit design
Tor et al. (2015)	National level swimmers (n = 11 M; n = 5 F, 20 ± 2)	Prone with arms extended over the head	0; 0.5; 1.0	 1.6 1.9 2.0 2.5	*0; 0.5; 1.0* 60; 61; 61 85; 81; 80 96; 88; 83 180; 143; 134 *(visual inspection)*	Not described	Quantifying the total drag force during the underwater phase
Zamparo et al. (2009)	Collegiate swimmers (n = 14 M; n = 11 F)	Prone with arms extended over the head	0	 0.78 1.00 1.22 1.42 1.62 1.80	*M; F* 14; 11 25; 19 36; 28 47; 40 60; 54 77; 73	*M; F* 24*; 19* 0.37**; 0.31**	Investigating the role of trunk incline and projected frontal area on drag

Table 3. List of the articles that used the *Flume method* to measure D_p, organized by author and containing all of the details related to the participants, protocol of measurement, D_p values, drag coefficient (Cd) or K coefficient (K), and purpose of the study.

References	Participants description (Sample size, Mean ± SD) (n, years)	Swimmer's position	Depth (m)	Swimmer's velocity ($m \cdot s^{-1}$)	D_p (N)	K* or Cd** coefficient	Purpose of study
Bixler et al. (2007)	Mannequin (n = 1)	Supine with arms extended over the head	0.75	1.49 1.75 2.02 2.25	32.10 45.97 62.77 78.11	Not described	To study the water flow and drag force in streamlined position
Chatard and Wilson (2003)	Swimmers (n = 5 M)	Prone with arms extended over the head	Not described	Mean 1.18	38.2	Not described	Metabolic and hydrodynamic responses of swimming in draft
Chatard and Wilson (2008)	Competitive swimmers (n = 10 M, 18 ± 3) (n = 4 F, 19 ± 3)	Prone with arms extended over the head	0	1.2 2.0	39.9 109.9	Not described	Investigating the effect of swimsuits on performance, drag and energy cost
Narita et al. (2017)	High level competitive swimmer (n = 6 M, 20.0 ± 1.0)	Prone with arms extended over the head	0	1.5	53	23.5* (v^2)	Evaluating the drag at various velocities and at full stroke
Roberts et al. (2003)	University Division I swimmers (n = 10 M, 20.2 ± 1.5)	Prone with arms extended over the head	0.40	2.0 2.5	77 101.9	Not described	Effects of swimsuit on physiological and biomechanical responses
Vennell et al. (2006)	Mannequin (n = 1)	Supine with arms extended over the head	0 to 1 (steps 0.1)	0.4 to 2.6 (steps 0.2)	80 to 180 (*visual inspection*)	0.25** to 0.4** up to 0.5 m depth (*visual inspection*)	Wave contribution on swimmers drag

decrement of the velocity of the streamline gliding swimmer by computing the deceleration force after a maximal push off from a fixed point. By measuring the instantaneous velocity according to time and fitting a hyperbolic velocity function to the data, the resistive forces can be determined.

Bilo and Nacthigall (1980) used, for the first time, such a method to assess *D* in birds and aquatic animals by measuring their initial and final velocities during a decelerating displacement from video recordings (i.e., where wings or fins did not produce any propulsive action) and then measured the body mass of the animals. Later, the method was extended to measurements of swimmers' drag (Kjendlie & Stallman, 2008).

In the literature, while Eik, Berthelsen, Caspersen, Pâkozdi, and Kjendlie (2008) reported consistently higher D_p values by the gliding decay method D_p measured by gliding decay, the towing or flume methods seemed to generally be comparable (Tables 2–4).

In the testing protocol of the gliding decay method, the swimmer submerges and pushes off a wall (or as an alternative he dives from a block) in a streamlined position. Pushing against the fixed point of the wall or block causes an early acceleration, followed by a progressive deceleration since only resistive forces continue to act against the swimmer's displacement. The resistive forces can be assessed by measuring the instantaneous deceleration and body mass of the swimmer. Cable accelerometers and underwater video-analysis are used to directly measure the swimmer's deceleration (Kjendlie & Stallman, 2008; Mollendorf et al., 2004).

When the body velocity changes during swimming and swimmers do not move at a constant speed, the flow pattern varies with time. In fact, under these conditions, an extra water mass is moved together with the swimmer in addition to his body mass and has to be taken into consideration as an important part of inertia (Vogel, 1994). Unfortunately, the added water mass cannot be precisely calculated because it depends on several factors, such as the area of impact and subject's hydrodynamic coefficient (Vogel, 1994). Some authors estimated the added water mass to correspond to approximately 28% of the swimmer's body mass (Barbosa et al., 2013; Caspersen et al., 2010), while other authors do not consider it (Mollendorf et al., 2004; Vilas-Boas et al., 2010).

With the gliding decay velocity method, Naemi and Sanders (2008) quantified the glide efficiency by advanced parametric fitting techniques to represent the displacement-time equation from the raw displacement-time data of the body, relating the hydrodynamic features of a human body while gliding in the streamlined position to the ability to maintain its velocity.

Because of its feasibility and low cost and time-consuming procedure, the gliding decay velocity method has a great advantage in measuring D_p compared to other methods used in the literature, which require more expensive and often inaccessible equipment. However, velocity variations and the need to precisely measure the added mass subsequent to the early acceleration are critical issues of this procedure. Furthermore, because of the difficulty in both managing the glide trajectory and tendency to rise to the surface when decreasing the velocity, it is challenging for swimmers to hold a stable depth while gliding during the testing protocol. All of these factors might affect D_p values when measured by the gliding decay velocity method (Barbosa et al., 2013).

Table 4. List of the articles that used the *Gliding decay method* to measure D_p, organized by author and containing all of the details related to the participants, protocol of measurement, D_p values, drag coefficient (Cd) or K coefficient (K), and purpose of the study.

References	Participants description (Sample size, Mean ± SD) (n, years)	Swimmer's position	Depth (m)	Swimmer's velocity ($m \cdot s^{-1}$)	D_p (N)	K* or Cd** coefficient	Purpose of study
Barbosa et al. (2013)	Regional and national level young swimmers (n = 12 M, 14.42 ± 1.24) (n = 11 F, 12.73 ± 0.79)	Prone with arms extended over the head	Self-selected depth	1.48 (*M*) 1.29 (*F*)	43.0 (*M*) 43.5 (*F*) *(visual inspection)*	0.35** (*M*) 0.39** (*F*) *(visual inspection)*	Speed fluctuation and drag force in young swimmers between genders
Barbosa et al. (2015)	Regional and national level young swimmers (n = 30 M, 13.59 ± 0.77) (n = 30 F, 12.61 ± 0.07)	Prone with arms extended over the head	Self-selected depth	1.5	48.92	0.26**	Comparison of swimmer drag collected with experimental and analytical procedures
Barbosa et al. (2015)	Regional and national level young swimmers (n = 13 M, 12.64 ± 0.81) (n = 12 F, 12.43 ± 0.78)	Prone with arms extended over the head	Self-selected depth	1.55	53	0.29**	Changes in hydrodynamic profile over a competitive season
Costa et al. (2015)	Well-trained swimmers (n = 6 M, 18.2 ± 4)	Prone with arms along the body (*A*); Prone with arms extended over the head (*B*)	0 to 1 (steps 0.1)	*B; A* nd; 1.1 nd; 1.2 1.3; 1.3 1.4; 1.4 1.5; 1.5 1.6; nd 1.7; nd	*B; A* nd; 32 nd; 38 34; 33 34; 42 38; 42 41; nd 47; nd *(visual inspection)*	*B**; A*** nd; 0.70 nd; 0.70 0.51; 0.50 0.49; 0.61 0.49; 0.48 0.45; nd 0.47; nd *(visual inspection)*	Comparison of swimmer drag collected with experimental and computational procedures
Kjendlie and Stallman (2008)	Young swimmers (*Y*) (n = 9 M, 11.7 ± 0.8) Adult swimmers (*A*) (n = 13 M, 21.4 ± 3.7)	Prone with arms extended over the head	0	1.25		0.74** (*Y*) 0.94** (*A*)	Comparing drag parameters in children and adult swimmers
Mollendorf et al. (2004)	University Division I swimmers (n = 7 M, 20.2 ± 0.5)	Prone with arms extended over the head	0	5.8 (*dive*) 2.7 (*push-off*)		0.978**	Differences in passive drag induced by swimsuit design
Morais et al. (2013)	Young swimmers (n = 12 M, 14.4 ± 1.2) (n = 11 F, 12.7 ± 0.8)	Prone with arms extended over the head	0.5 to 1	0.56 to 0.84	12.88 to 69.93	Not described	To verify the suitability of gliding test to estimate the swimmers' water resistance
Vilas-Boas et al. (2010)	National level swimmers (n = 6 M, 18.2 ± 4.0) (n = 6 F, 17.3 ± 3.0)	Prone with arms along the body (*A*); Prone with arms extended over the head (*B*)	Self-selected depth	1.37	31.67 (*B*) 46.25 (*A*)	0.46** (*B*) 0.66** (*A*)	Comparing the first and second gliding positions of breaststroke underwater stroke

Computational fluid dynamics (CFD) method

When considering the swimmer as an object whose shape does not change while measuring D_p, movements can be simulated in a graphic environment. The computational fluid dynamics method (CFD) is a numerical technique for calculating D_p in an alternative way from the experimental approach.

CFD builds a computer-based model composed of 2D or 3D cells (mesh of cells) to compute the effects of the water flow around the swimmer's body and to study the pressure values that are generated at different velocities (Bixler et al., 2007).

CFD modelling was used for the first time in the 1990s to study the flight of insects and birds (Liu, Wassersug, & Kawachi, 1997). Later, CFD modelling was applied to compute the forces acting on moving aerodynamic and hydrodynamic models (Cheng & Chahine, 2001). The earliest studies in swimming applying the CFD method were conducted by Bixler et al. (2007), who performed a 2D analysis of the water flow around swimmers' limbs. Marinho et al. (2009) was the first to calculate D_p by a 2D CFD model and found that gliding in the prone position differs from gliding on the side. 3D analysis guarantees a higher level of accuracy than that of 2D modelling (Bixler et al., 2007), which seems to be inadequate for correctly evaluating drag forces because of overestimation. As a consequence, 3D modelling is necessary for swimming analysis (Zaïdi et al., 2010).

The CFD method facilitates swimmer reproduction through i) non-realistic models using basic geometric shapes; ii) quasi-realistic models by artificially approximating the body shape; and iii) realistic models by scanning and generating a 3D reproduction of the swimmer's body. The values of D_p computed by CFD have been shown to be comparable to data measured by experimental methods (Marinho et al., 2011, 2009; Vilas-Boas et al., 2010) (Table 5). Although this procedure requires a very detailed reproduction of the swimmer's body as well as specific cinematics to be accurate and precise (Costa et al., 2015), CFD has been demonstrated to be extremely adequate for measuring D_p in the streamline position (Bixler et al., 2007).

In the CFD procedure, the geometry of the swimmer's body is acquired by 3D scanning or it is virtually reproduced by computer-aided drafting (CAD) based on the anthropometrical characteristics of the most common swimmer, further modelling a surface mesh. The accuracy of the smoothing process during the generation of the graphical reproduction of the swimmer's body is particularly important because of its relevant outcomes on the subsequent computation procedure. Key points (shoulders, hips, knees, ankles) are set on the model and are used as points of reference for cinematic implementations. The generation of the body model can also provide body part positions or movements, depending on the study design and purpose. Thereafter, the model is placed in a computational-simulated environment that reproduces the fluid flow around the human body, and by iterative computerized calculations, the flow equations are solved.

In swimming analysis, application of a numerical simulation offers interesting advances to reduce time and cost of D_p measurements. Experimental approaches of D_p assessment are affected by several issues that are mainly related to the protocol's design and the capacity of swimmers to hold the gliding position while performing the test (Bixler et al., 2007). In this regard, the computerized computational procedure offers great advantages compared to other methods, although CFD is highly dependent and limited based on the model construction and theoretical assumptions used.

Conclusion

This study reviewed the state of the art in measuring swimmers' D_p. Methods to measure D_p were described and analysed, highlighting their respective advantages and applications.

The towing method seems to be the first and main scientific tool to investigate the drag of swimmers. This method measures the resistive forces of a towed swimmer in a stable position by a dynamometer. The towing method is the most common method because of its consistent advantage in validity and reliability, as has been widely demonstrated in the literature. The only limitation of this procedure is its accuracy: dynamometers barely detect small variations of D_p that possibly come from corrections made by swimmers while gliding to maintain the stable position, exposing researchers to experimental design issues.

The first studies to use the flume and gliding decay methods were conducted after the 2000s. In the flume method, which is comparable to wind tunnel systems, measurement of swimmers' drag is similar to the towing method, but without displacement of the swimmer with respect to the environment because the water flow generated by engines is moving while the swimmer is steady and linked to a dynamometer. Although the literature has confirmed the validity of this procedure, expensive and hard to find equipment are needed. In contrast, the gliding decay method is easy to use and requires simple instruments, such a speedometer, to measure the deceleration of the swimmers after a push off. Unfortunately, limits have been described for this method because of the difficulty in estimating the water added mass that occurs when the velocity of the swimmer changes, such as during a push off.

The most recent method validated in the literature since the end of the 2000s is computational fluid dynamics. The high accuracy of this computational method is the determining factor of this procedure, which has been confirmed by several comparative studies with other techniques. Furthermore, the computational system can reduce the time necessary for measurements, simplifying the experimental set-up. However, high reproducibility of the swimmer's body and the fluid characteristics are essential to ensure its accuracy, revealing limitations associated with the process of model construction and for the theoretical assumptions of this procedure.

By measuring D_p, investigations aim to identify finding most efficient passive gliding position and to determine the best performing morphology, hydrodynamic profile and physique shape of swimmers. For this reason and because of the importance of gliding in several phases of a swimming race, the head position, trunk incline and depth of the streamline gliding itself are the most explored topics by these methods. In addition, physiological and biomechanical positive effects as a result of wearing equipment, such as caps and suits, have been widely investigated, considering D_p as an indicator of the performance.

Table 5. List of the articles that used the *CFD method* to measure D_p, organized by author and containing all of the details related to the participants, protocol of measurement, D_p values, drag coefficient (Cd) or K coefficient (K), and purpose of the study.

References	Participants description (Sample size, Mean ± SD) (n, years)	Swimmer's position	Depth (m)	Swimmer's velocity (m • s^{-1})	D_p (N)	K* or Cd** coefficient	Purpose of study
Barbosa et al. (2018)	Model of an Olympic male swimmer (n = 1)	Prone with arms extended over the head	0.75	1.3 1.5 1.7 2.0 2.2 2.5	45 56 76 94 123 144	0.70** 0.68** 0.65** 0.64** 0.63** 0.62**	Comparing the passive drag by numerical simulation and analytical procedure
Bixler et al. (2007)	Model of an elite male swimmer (n = 1)	Supine with arms extended over the head	0.75	1.50 1.75 2.00 2.25	31.58 42.74 55.57 70.08	0.302** 0.300** 0.298** 0.297**	To study the water flow and drag force in streamlined position
Costa et al. (2015)	Model of a swimmer (n = 1)	Prone with arms along the body (A); Prone with arms extended over the head (B)	0.90	*B; A* nd; 1.1 nd; 1.2 1.3; 1.3 1.4; 1.4 1.5; 1.5 1.6; nd 1.7; nd	*B; A* nd; 18 nd; 20 18; 22 20; 25 23; 29 26; nd 28; nd	*B**; A*** nd; 0.28 nd; 0.31 0.30; 0.31 0.30; 0.40 0.30; 0.43 0.30; nd 0.30; nd	Comparing the swimmer's drag collected with experimental and computational procedures
Li and Zhan (2015)	Model of an adult male swimmer (n = 4)	Prone and arms extended over the head. Body shape: inverted triangle (*A*), inverted trapezoid (*B*), rectangle (*C*), oval (*D*)	0.2	1.2 1.4 1.6 1.8 2.0 2.2	*A; B; C; D* 25.16; 27.64; 29.33; 32.97 30.71; 33.19; 36.46; 39.92 44.68; 48.15; 52.14; 57.15 55.35; 59.03; 67.33; 72.25 66.83; 71.32; 79.7; 90.25 81.88; 84.76; 93.49; 103.62	Not described	Analysing the hydrodynamic characteristics of different swimmers' shapes
Marinho et al. (2009)	Model of an elite male swimmer (n = 2)	Prone with arms along the body (*A*); Prone with arms extended over the head (*B*)	1.8	1.6 1.7 1.8 1.9 2.0		*A**; B*** 0.82; 0.48 0.78; 0.47 0.76; 0.43 0.76; 0.43 0.74; 0.43	Analysing the effect of body position on the drag of underwater gliding
Marinho et al. (2011)	Model of a male national level swimmer's group (n = 15, 20.02 ± 1.37)	Prone with arms along the body (*A*); with arms extended over the head in prone (*B*), supine (*C*), lateral (*D*) position	0.90	1.6 1.7 1.8 1.9 2.0	*A; B; C; D* 69; 59; 57; 36 73; 63; 61; 40 77; 67; 65; 44 81; 71; 69; 49 85; 75; 73; 53 *(visual inspection)*	*A; B; C; D (**)* 1.06; 0.91; 0.88; 0.57 1.00; 0.87; 0.84; 0.56 0.95; 0.83; 0.81; 0.55 0.90; 0.79; 0.77; 0.54 0.85; 0.75; 0.73; 0.53	Effects of different body positions during gliding on drag forces
Novais et al. (2012)	Model of an Olympic swimmer (n = 1)	Prone with arms extended over the head	*0; 0.25; 0.5; 0.75; 1*	1.5 2.0 2.5	*0; 0.25; 0.5; 0.75; 1* (*Depth*) 52; 63; 58; 57; 56 89; 98; 97; 94; 93 120; 148; 146; 144; 143	*0; 0.25; 0.5; 0.75; 1* **(**)** (*Depth*) 0.62; 0.76; 0.69; 0.68; 0.67 0.60; 0.66; 0.65; 0.64; 0.63 0.52; 0.64; 0.63; 0.62; 0.62	Effects of depth on drag during gliding
Pacholak et al. (2014)	Model of a female butterfly swimmer (n = 1)	Prone with arms extended over the head	Not described	1.18	15.9	Not described	Demonstrating the formation and interaction of vortices on swimmer's body

(*Continued*)

Table 5. (Continued).

References	Participants description (Sample size, Mean ± SD) (n, years)	Swimmer's position	Depth (m)	Swimmer's velocity ($m \cdot s^{-1}$)	D_p (N)	K* or Cd** coefficient	Purpose of study
Silva et al. (2008)	Model of an elite national level swimmer (n = 1)	Prone with arms extended over the head	Not described	1.6 1.7 1.8 1.9 2.0		0.917** 0.883** 0.857** 0.833** 0.811**	Effect of drafting distance on the swimmer's drag
von Loebbecke et al. (2009)	Model of a female Olympic-standard swimmer (n = 1)	Prone with arms extended over the head	Not described	1.0	19.7		Computational modelling of the hydrodynamics of swimming strokes
Zaïdi et al. (2008)	Model of an elite female swimmer (n = 1)	Prone with arms extended over the head	1.5	1.4 2.2 3.1	28 62 130 *(visual inspection)*	0.28** 0.27** 0.27** *(visual inspection)*	Effect of head position on performance
Zaïdi et al. (2010)	Model of a national-level female swimmer (n = 1)	Prone with arms extended over the head	1.5	1.4 2.2 3.1	28 62 130	Not described	Calculating the drag forces using turbulence models
Zhan et al. (2015)	Model of a national male swimmers' group (n = not described)	Prone with arms extended over the head	0.90	1.00 1.20 1.42 1.70 1.90 2.03	30 45 65 80 110 135 *(visual inspection)*	Not described	To study the passive drag on the water surface

The procedures for measuring passive drag that have been validated in the literature set a passive drag coefficient (Cd) of the swimmer at the surface that is independent of the velocity of the displacement variable, very close to 0.6 (K coefficient close to 25), according to the swimmer's gender and level. Considering the absolute value of passive drag is dependent on the squared displacement velocity, researchers in this field have agreed to consider a quadratic relationship with a velocity exponent very close to 2.0.

In conclusion, evaluation of the methods for measuring passive drag can be considered to be a worthwhile endeavour for coaches and practitioners to evaluate and determine the drag of their swimmers. To date, the towing method seems to be the most commonly used method for measuring D_p because of its easier assessment procedure compared to flume method and its lack of dependence on the theoretical assumptions involved in the gliding decay and CFD methods.

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No potential conflict of interest was reported by the authors.

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