"Selecting the right tool for the job" a narrative overview of experimental methods used to measure or estimate active and passive drag in competitive swimming.

Gina Sacilotto[1], Ross Sanders[2], Tomohiro Gonjo[3], Daniel Marinho[4], Bruce Mason[5], Roozbeh Naemi[6], João Paulo Vilas-Boas[7], Christopher Papic[8]

[1]Carlile Swimming, Sydney, Australia.
[2]Faculty of Health Sciences, The University of Sydney, Sydney, Australia.
[3]Department of Rehabilitation and Sport Sciences, Bournemouth University, Dorset, UK.
[4]Research Center in Sports Science, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal.
[5]Asppen Company, Canberra, Australia.
[6]School of Life Sciences and Education, Staffordshire University, Stoke-on-Trent, UK.
[7]Faculty of Sport, University of Porto, Porto, Portugal.
[8]Exercise and Sports Science, School of Science and Technology, University of New England, Armidale, Australia.

Abstract

Free-swimming performance depends strongly on the ability to minimise resistive drag. Therefore, estimating resistive drag (passive or active) may be important to understand how free-swimming performance can be improved. The purpose of this narrative overview was to describe and discuss experimental methods of measuring or estimating active and passive drag relevant to competitive swimming. Studies were identified using a mixed-model approach comprising a search of SCOPUS and Web of Science data bases, follow-up of relevant studies cited in manuscripts from the primary search, and additional studies identified by the co-authors based on their niche areas of fluid dynamics expertise. The utility and limitations of the methods of measuring active and passive drag were critically discussed with reference to primary research domains in this field, 'swimmer morphology' and 'technique analysis'. This review and subsequent discussions provide implications for researchers when selecting an appropriate method to measure resistive forces (active or passive) relevant to improving performance in free-swimming.

Keywords: Swimming, Kinematics, Kinetics, Force Measurement

Introduction

Competitive swimming is a highly popular sport worldwide. With the difference between winning and losing in the current era, sometimes being as little as one-hundredth of a second, researchers seek to understand how small improvements in performance can be achieved by swimmers. A swimming race consists of start, free-swimming, turn(s) and finish phase (Guimaraes & Hay, 1985). The ability to reduce time spent in each of these phases is a primary goal for most research investigations in competitive swimming. Free-swimming is the phase in which most time is spent during a race. Besides free-swimming, pure gliding phases are also relevant to the total race time, normally included in start and turn phase times for race analysis purposes. Therefore, improvements in free-swimming, as well as in gliding actions, will have a major bearing on overall performance (Cossor and Mason, 2001; Veiga et al., 2013).

Performance during the free-swimming phase depends on propulsive and resistive forces (Toussaint, 2000; Toussaint et al., 2002). Propulsion is generated by active movements of the swimmer to move through the water. However, as a consequence of the propelling actions and physiological supporting movements, such as breathing, resistive forces are encountered (active drag) that differ from the forces acting when in a passive gliding position (passive drag) (Benjanuvatra et al., 2001; Havriluk, 2005; Toussaint & Truijens, 2005is; Chatard et al., 1990). Hydrodynamic drag comprises three components of drag force associated with dynamic swimming motion. These components are known as wave drag (or 'wave making drag'), form drag (sometimes referred to as 'pressure drag' or 'frontal drag'), and friction drag (sometimes referred to as 'surface drag' or 'skin friction') (Benjanuvatra et al., 2001; Kolmogorov et al., 1997; Zamparo et al., 2009). It is generally accepted that friction drag has a linear relationship with swimming velocity, that pressure drag has the most relevance at low and mid swimming velocities and the relationship is usually expressed as a square of swimming velocity, and that wave drag exerts its main contribution at high velocities with a cubic relationship (Lyttle et al., 1999, Pendergast et al., 2005). These components of drag depend on several factors including the transient pressure points associated with the water flow, the shape of the body and the manner in which the shape of the immersed body changes during a swimming stroke cycle, the smoothness of the body, and length of the body surface in contact with the water. Consequently, a swimmer may be able to reduce drag forces (passive or active) by changing body geometry during gliding, stroking and underwater body movements such as the kick and pull (Papic et al., 2021). This can be done by using special swimsuits, nutritional manipulation, strength training and by improving swimming technique (Marinho et al., 2009).

When investigating resistive forces in swimming, and factors that influence resistive force, researchers often have a difficult task of deciding which experimental approach they should utilise [numerical solutions are out of scope of this overview due to complexity and operational difficulties to a swimmer's specific customized forces estimation, particularly for active conditions. Numerical methods include Computational Fluid Dynamics (CFD) (Marinho et al., 2009; von Loebbecke et al., 2009) and Smoothed Particle Hydrodynamics – SPH – (Cohen et al., 2009)]. Methods are selected based on one or more of the following hydrodynamic drag research domains: (i) body segment and/or anthropometric variable(s) being assessed (swimmer morphology); (ii) swimming technique and (iii) apparel to be studied, as well as on (iv) the accuracy and validity of the method, (v) the practicality and availability of equipment or (vi) the feasibility of the experimental design. Unfortunately, due to the inexistence of a 'ground truth' method, the validity and accuracy of experimental methods are difficult to establish. A possible future solution for this issue may rely on comparing experimental data with realistic animated numerical simulations (Costa et al., 2015).

Experimental methods can be categorised into passive drag and active drag measurements. In general, active drag methods are preferred as they consider free-swimming actions. However, if the research question to be answered is related to the gliding phases after starts and turns, passive drag assessing methods may be preferable. Interestingly, Chatard et al. (1990) showed that passive drag may discriminate between swimmers of different proficiency levels, despite most of the swimming event being performed with active swimming actions. Zamparo et al. (2009) proposed a method of estimating active drag based on the product of the swimming velocity of interest and the speed specific passive drag (Dp/v^2), multiplied by the ratio between active and passive frontal areas. Despite considerable covariance between active and passive drag outcomes, there is a lack of consensus on optimal methods of assessing drag force which are relevant to free-swimming performance. Therefore, the aim of this review was to outline current experimental methods used to assess active and passive drag in swimming and to explore the utility and limitations of these methods, stratified by relevant swimming hydrodynamic drag research domains. Greater understanding of the trade-off between a method's utility and limitations will provide further clarity on the appropriateness of experimental tools used to investigate active and passive drag within these domains.

Methods

A mixed model of three search methods was applied to identify papers relevant to the discussion of methods used to assess active and passive drag in human swimming. Firstly, a primary search of SCOPUS and Web of Science data bases was conducted using the following search terms: swimming AND active drag, passive drag, hydrodynamic, resistive forces, morphology, and swimming technique. Abstracts were read to assess eligibility prior to conducting a full review of each manuscript. Second, additional manuscripts were identified from citations in relevant manuscripts that were selected for full review in the initial search. Third, relevant studies that were not captured in the previous steps were identified by the contributing authors based on expertise in their niche research areas of active and passive drag. Given that the review was designed to present information about experimental tools used to assess active and passive drag, studies were included if they presented information about those methods in a way that was clear and rigorous. Studies were therefore included in the review if they met the following criteria: i) human study; ii) clear description of the experimental tool including product information and setup specifications; iii) description and rationale of the drag force outcome measure including biomechanical assumptions. Additionally, data that were relevant to the discussion on the utility and limitations experimental tools were extracted from studies, including: reliability analyses and drag force measurement differences between experimental methods. In view of the need to provide some background of historical progression of the development of the tools, there were no time constraints applied to the primary search. No other inclusion or exclusion criteria were applied. Consequently, relevant proceedings papers were also included.

Included studies were organised into an ‘overview of active drag methods’ followed by an ‘overview of passive drag methods’. Those overviews facilitated a critical discussion of the implications for practice, organised into research domains ‘swimmer morphology’ and ‘technique analysis’. Each section was then divided to discuss the utilisation of passive and active drag methods in these areas.

Results

A synthesis of the methods of passive and active drag methods discussed on this narrative overview of extant literature is presented in Figure 1.

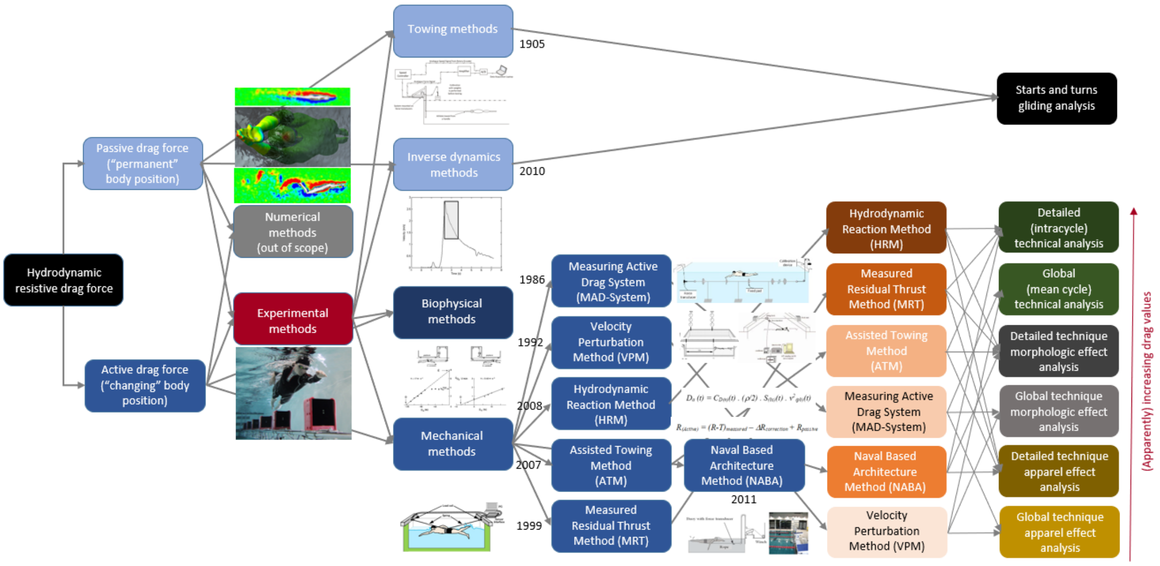

Figure 1. Diagrammatic synthesis of the passive and active methods discussed. Chronology, possible inconsistency of drag value results considering absolute values published and applications regarding research questions are highlighted.

Overview of Active Drag Methods

Active drag is affected by changes in the body’s shape, particularly frontal surface area, and movement of the body segments which are consequently influenced by, and simultaneously a cause of, inefficient or uneconomical swimming techniques (Clarys, 1979; Zamparo et al., 2009). Kolmogorov et al. (1997)

provided evidence that the smaller active drag coefficient of elite swimmers than their sub-elite counterparts in some swimming strokes (female breaststroke, male butterfly and front crawl) was due to elite swimmers having higher stroke length to stroke rate ratios associated with higher technical proficiency. Therefore, swimming fast depends both on the athlete's body shape and dimensions as well as on the ability of a swimmer to reduce active drag through proficient stroke technique and apparel, which will assist in generating and maintaining a higher swim velocity.

A previous review on active drag assessment methods was published by Wilson and Thorp (2003). The early method of determining active drag in free-swimming was based on the relationship between the energy expenditure of swimming, the swim speed and body drag (di Prampero et al., 1974). It became known as a biophysical approach. Di Prampero et al. (1974) identified a linear relationship between added positive and negative (resistive) forces and oxygen consumption at constant submaximal swim velocities. An extrapolation of the regression line to "zero" added force was used to identify active drag at that particular constant velocity. This pioneering work was the catalyst for subsequent investigations of active drag which followed a very similar approach (Clarys, 1979). The biophysical method, despite very creative, is difficult to implement, imposing various external ecological constraints to the swimmer that surely hinder performance.

Experimental mechanical methods used to estimate active drag, in succession to the biophysical precursor, include the Measurement of Active Drag System (MAD-System) (Hollander et al., 1986), the Velocity Perturbation Method (VPM) (Kolmogorov & Duplishcheva, 1992; Xin-Feng et al., 2007), the Assisted Towing Method (ATM) (Alcock and Mason, 2007), the Naval Based Architecture method (NABA) (Webb et al., 2011), the Method of Instantaneous Hydrodynamic Reaction or Hydrodynamic Reaction Method (HRM) (Kolmogorov, 2008) and the Measured values of Residual Thrust (MRT) while swimming in a flume (Narita et al., 2017) developed from a similar method established by Takagi et al., (1999). The MAD-System, which was engineered in 1986 by a group of Dutch scientists, requires the swimmer to pull on submerged pads instrumented with force transducers (Hollander et al., 1986). Whilst the MAD-System is the most frequently observed method in the extant literature, it is limited by measuring only the front crawl arm pull forces as the swimmer's legs are bound. Also, despite the similarity of electromyography patterns obtained during MAD-System and normal front crawl swimming (Clarys et al., 1988), it is questionable whether the pulling on the paddles replicates the normal swimming action or restricts normal stroke mechanics (Sacilotto et al., 2014). Schreven et al. (2013) further assessed the reliability of the set inter-pad distances of the MAD-System based on anthropometric characteristics of a small sample of participants (n=11) swimming at sub-maximal speed and concluded that a fixed distance could be used. Whilst adding to the scope of studies utilising the MAD-System, it should be noted that the translatability of this finding to swimming in a competition setting requires further investigation.

The VPM method was first published in 1992 by Russian scientists (Kolmogorov & Duplishcheva, 1992), and revisited some years later by a Chinese research group with a similar conceptual approach (Xin-Feng et al., 2007). The VPM method estimates the active drag by calculating the difference in velocity between a free-swimming condition and a resisted swimming condition, whilst incorporating a known resistant force (the resistance of a hydrodynamic body or a resistive cable attached to the swimmer and towed behind them). The VPM relies on two assumptions: (i) the athlete swims with at a velocity that is constant between the stroke cycles, and (ii) the athlete produces equal power output efforts in both conditions. These assumptions rely on the swimmers' capability and compliance to reproduce equal power output in both the free-swim and resisted conditions and, in the absence of a 'ground-truth' method, its appropriateness cannot be evaluated. Researchers from the Australian Institute of Sport accepted the two assumptions and modified the testing protocol to calculate active drag using the mean velocities in free-swimming and assisted tow swim conditions (Alcock & Mason, 2007). Authors solved the Newtonian drag equation assuming that it varies with v^2, which means that there might be an error when the contribution of the wave drag to the total active drag is large because the wave drag is proportional to the cube of the velocity (Vennell et al., 2006).The ATM has been used to investigate intra-stroke velocity fluctuations, as athletes are able swim with close to normal stroke mechanics (Mason et al., 2011). In addition, the researchers captured and displayed instantaneous resultant force-time profiles across the entire stroke cycle, adding a new approach to the assessment of this technique (Mason et al., 2013; Mason et al., 2012; Mason et al., 2011; Sacilotto et al., 2013; Sacilotto et al., 2015). Such force-time profiles are presented in conjunction with front and side video images of the swimmer to assess technique inefficiencies and enable coaches and swimmers to refine technique with the aid of immediate feedback to reduce active drag. Based on the extant literature, the ATM has been applied to assess the impact of technique on active drag only in front crawl and backstroke and so there are no data indicating its potential efficacy with respect to estimating active drag in butterfly and breaststroke swimming.

Kolmogorov (2008) modified the VPM method to allow for active drag assessment at submaximal speeds and to accommodate intracyclic active drag variations due to changes in body geometry that are associated with free-swimming intersegmental movements. Kolmogorov published this method for the first time in the year of 2008 in the Russian Journal of Biomechanics, without specifically naming it, and without further application in the international scientific scene, with the exception of recent work published by Kolmogorov, Vorontsov and Vilas-Boas (2021). According to the original text, this method can be named as “Hydrodynamic Reaction Method” (HRM), and is based on the Equation 1:

$$D_a\,(t) = C_{D(n)}(t)\ .\ (\rho/2)\ .\ S_{(bs)}(t)\ .\ v^2_{(pb)}(t) \qquad \text{(Equation 1)}$$

Where: $D_a\,(t)$ refers to instantaneous frontal component of active drag, or pressure drag, $C_{D(n)}(t)$ is the instantaneous value of the dimensionless coefficient of the frontal component of the active drag force, corresponding to the unsteady mode of motion of the body, ρ is the density of water (kg.m^{-3}), $S_{(bs)}(t)$ is the instantaneous value of the characteristic hydrodynamic size of the subject’s body (m^2) and $v_{(pb)}(t)$ stands for the instantaneous value of the velocity of a point on the surface of the human body (trunk) when swimming (m.s^{-1}).

The HRM method consists of solving the drag equation for Newtonian fluids in relevant instants of the stroking cycle of each swimming technique while considering the intra-cyclic speed fluctuation profile. To determine $v_{(pb)}(t)$, a Doppler speedometer was used; to assess $S_{(bs)}(t)$, a three-dimensional kinematic analysis of the movement of all the main segments of the human body was used, based on underwater and surface video records; ($S_{(bs)}(t)$ was defined as 2/3 of the immersed volume of the subject’s body at a given time instant (m^2), not including the projected areas of the body segments which, at a given moment of the biomechanical cycle, are the movers and have a negative velocity with respect to the direction of translational motion of the body’s center of mass); to evaluate $C_{D(n)}(t)$, a method of full-scale hydrodynamic tests of a swimmer and respective special anthropomorphic models in conditions of stationary and non-stationary movement was implemented in a water tunnel. A total discretization of the stroke cycle into 16 to 25 transient positions (discreteness of 0.06 s) was conducted based on the cycle duration.

The VPM method was used as a criterion to validate the Naval Based Architecture method (NABA presented by Webb et al (2011)). The NABA method is a conceptually similar approach to the ATM. Swimmers swim at maximal velocity, and are then towed at velocities 5, 10, and 15% higher than maximum, assuming that stroke rate increases proportionally to velocity in towing conditions. Towed passive drag is also assessed. The NABA method relies on the Equation 2 to estimate active drag:

$$R_{(Active)} = (R\text{-}T)_{measured} - \Delta R_{correction} + R_{passive} \qquad \text{(Equation 2)}$$

$R(active)$ stands for active drag, $(R\text{-}T)_{measured}$ for the measured resultant force between active drag and thrust (the tension at the towing cable), $\Delta R_{correction}$ for the correction value of passive drag back to actual swimming velocity, and $R_{passive}$ for towed passive drag, or naked hull drag.

Results of VPM and NABA were similar. In both methods, an equal power assumption for the different testing conditions was accepted.

Using a swimming flume, a group of scientists from Japan have developed a method to estimate active drag in swimming using the Measured values of Residual Thrust (MRT-Method) (Narita et al., 2017; Gonjo et al., 2020), which was developped from a method originally proposed by Takagi et al. (1999). The relationship between propulsive and resistive forces in swimming was used to design this new method of active drag analysis. This method was developed to provide an alternative to the VPM and ATM designs, which require maximal swimming velocities to derive hydrodynamic resistance. The difference between hydrodynamic resistance and propulsive force was denoted as residual thrust, which was obtained in a flume at nine flow velocities (while the swimmer maintains the same motion). The residual thrust data obtained from the multiple trials (y) are plotted against the flow velocity (x), and active drag force can be mathematically computed by extrapolating the flow velocity–residual thrust curve and obtaining the y-intercept (the residual thrust at zero flow velocity corresponds to the active drag). Previous limitations of restrictive stroke analysis (the arm-only front crawl restriction) and velocity (applicable for only the maximum effort swimming) in other methods used to assess active drag in swimming are not considered a restriction within the MRT-method. In other words, theoretically this method can be applied to any swimming strokes at a wide range of swimming intensities. Therefore, the assessment of the MRT-method's reliability and validity are of interest in research groups world-wide (Gonjo et al., 2020; Narita et al., 2018a, 2018b). Particularly, the assumption that swimmers can reproduce the same motion regardless of the environmental change (i.e. flow velocity and the special condition of swimming in a flume) should be further explored.

Overview of Passive Drag Methods

Methods of obtaining passive drag include those utilising towing or fixing devices (considering pool or flume conditions) and inverse dynamic methods to assess resistive force of the swimmer's body in the absence of active swimming actions. Scurati et al. (2019) performed a thorough systematic review of passive drag assessment methods. The pioneer work in the field was conducted by DuBois-Reymond (1905), where swimmers were towed from a rowing boat and hydrodynamic resistance was measured through a dynamometer. Amar (1920) observed, for the first time in swimmers, that passive drag is related to the towing velocity squared. Some years later, Karpovich (1933) developed the 'Resistograph', a device using an electrical motor to accurately control the towing velocity, and characterized the 'K' factor of the relationship $D = Kv^2$. More recently, a strain gauge was attached to a special towing structure (Clarys, 1978, 1979; Clarys and Jiskoot, 1975), or to a segment of the towing rope (Chatard et al., 1990) to assess the force required to tow the swimmer at a constant velocity in a passive condition. The relevance of passive drag for discriminating between competitive levels of swimmers was shown by Chatard et al. (1990) and a discussion on how passive and active drag are related was initiated by Clarys (1978, 1979), and further continued by Takagi et al (1999) and Zamparo et al. (2009). Passive drag force of swimmers in the streamlined body position was more recently analysed using a uniaxial load cell consisting of four strain gauges attached to the towing rope (Lyttle et al., 2000). Lyttle and colleagues (2000) suggested that this method had small coefficients of variation (CV) in drag force values (≤ 2.7%) and was considered reliable for determining hydrodynamic resistance of swimmers. The CV values reported may be explained by difficulties in controlling body position during the towing process, which may suggest that increased attention be paid to inverse dynamics approaches. A limitation of passive towing methods where the load cell is position in front of the swimmer's body is that it can affect fluid flow characteristics before reaching the swimmer due to its proximity to the towing handle.

The force required to tow a swimmer can also be determined by an inbuilt dynamometer in the towing device (Tor et al., 2015). An advantage of the force-measuring device positioned out of the pool, compared with a load cell attached to the towing rope, is that it does not influence flow characteristics near the swimmer. Regardless of whether the towing protocol uses a load cell or dynamometer to determine hydrodynamic resistance, passive towing experimental studies use an adjustable pulley system fixed to the pool wall. The pulley system can be submerged to a desired depth allowing for towing to be parallel to the water surface. As a result, the effect of the depth, morphology, posture, and velocity on passive drag can assess passive drag at the glide depths attained during the start and turn. For example, passive towing at a range of depths revealed a significant increase in hydrodynamic resistance near the surface of the water, due to the wave making processes (Jiskoot and Clarys, 1975; Lyttle et al., 1998; Tor et al., 2015; Vennell et al., 2006). The effect of raising the head was also analysed as one of the first studies of the effects of posture on drag force (Clarys and Jiskoot, 1975). The body position of the swimmer during passive drag analysis methods is predominately performed in the streamlined body position. Consequently, hydrodynamic outcomes from these studies have implications for the underwater phases of the start and turn when the streamlined body position is used to minimise hydrodynamic resistance.

Inverse dynamics analysis of 2D video or speedometer data to derive resistive force outcomes of the streamlined body is an alternative to direct force measurement. Hydrodynamic resistance of swimmers during the glide phase can be derived using the gliding velocity decay method (Barbosa et al., 2015a; Barbosa et al., 2015b; Vilas-Boas et al., 2010). In the study of Barbosa et al. (2015b), swimmers performed a maximal underwater wall push off and horizontal glide in the streamlined body position, without initiating upper or lower limb swimming actions. Instantaneous acceleration of the hip was derived from kinematic data. Passive drag (D_p) was calculated based on Newtonian physics (Equation

3), using the swimmer's body mass (m, kg), estimated added fluid mass (m_a, kg), and acceleration over the duration of interest ($m.s^{-2}$), corresponding to a pure gliding phase.

$$D_p = (m + m_a) \cdot a \qquad \text{(Equation 3)}$$

Passive drag values derived from the gliding velocity decay method can then be used to compute the drag coefficient (C_d) using passive drag force (D_p), fluid density (ρ, kg/m^3), Frontal Surface Area (A, m^2) and mean velocity (v, m/s) (Equation 4) (Barbosa et al., 2015b; Vilas-Boas et al., 2010).

$$C_d = \frac{D_p \cdot 2}{\rho \cdot A \cdot v^2} \qquad \text{(Equation 4)}$$

Both direct force measurement methods and inverse dynamic methods of passive drag analysis can be used to compute the drag coefficient. The coefficient indicates how effective the swimmer is at minimising passive drag and is influenced by body shape, surface characteristics, and posture in the water (Naemi et al., 2010). Consequently, the drag coefficient can be used to assess the effect of morphological characteristics of bodies of different size and mass, on hydrodynamic resistance (Alexander, 1990). Webb et al. (2015) compared the towing and the inverse dynamics methods and found that they show similar sensitiveness to changes in garment and hair removal, but higher drag coefficients were found for the towing method, attributed to difficulties in controlling gliding position, which may suggest some advantages of the inverse dynamics approach.

A method of calculating glide distance, irrespective of initial velocity, was proposed to measure the efficiency of swimmers' gliding (Starling et al., 1995). This was conducted before the inverse dynamic approaches described above. Glide distance (m) was calculated as the area under the velocity-time curve, for a normalised initial velocity, to compare glide efficiency within- and between-swimmers.

In a similar line of reasoning, Naemi and Sanders (2008) developed the Hydro-kinematic method in which the deceleration pattern of a swimmer during an underwater glide was used to calculate a glide efficiency parameter that was inversely proportional to hydrodynamic resistance and directly proportional to inertia. In this method, a displacement function was first derived from the equation of motion of the body during a horizontal rectilinear glide (Naemi & Sanders, 2008). This function was then fitted to the position-time data of the body during a rectilinear horizontal glide enabled glide efficiency to be quantified as the 'glide factor' (Naemi & Sanders, 2008). The glide efficiency accounts for both the inertial (the added mass of water in addition to the effect of the swimmer’s own body mass) and the resistive characteristics of a body.

Discussion and Implications

Utility and limitations of passive drag methods

Hydrodynamic resistance outcomes derived from passive drag methods have been found to have significant relationships with anthropometric and morphological characteristics in several studies (Chatard et al., 1990; Clarys, 1979; Cortesi et al., 2020; Kjendlie & Stallman, 2008; Naemi et al., 2012; Pendergast et al., 2005; Zamparo et al., 2009). Passive drag measures obtained from towing methods provide consistent hydrodynamic outcomes with little effort to collect data (Scurati et al., 2019). To evaluate the effect of morphology on hydrodynamic resistance, passive resistive force and morphological outcomes are often derived independent of one another (Clarys, 1979). For instance, analysis of anthropometric, morphological and composition (fat and fat-free mass) characteristics of the body can be performed on swimmers adopting a static posture on land, mimicking a glide posture (Cortesi et al., 2020). Cortesi et al. (2020) determined passive drag using an experimental passive towing technique among sixty young competitive swimmers. Results from this participant sample indicated that passive drag was strongly correlated with body mass, biacromial- and bi-iliac-breadth, streamline chest circumference and breadth, which was suggested to be useful for talent identification in swimming with reference to the gliding performance. The relationship between morphological outcomes and passive drag can then be evaluated statistically to provide insight into optimal drag profiles and talent identification protocols.

The postures adopted by the swimmers during passive towing assessment simulate postures used in glide phases of competitive swimming and therefore these methods may be well suited to analysis of the glide phases of competitive swimming. However, one limitation of passive towing methods is that the effect of body inertia on hydrodynamic resistance cannot be directly assessed (Naemi et al., 2010), especially if added mass is not determined and, inclusively, if only estimated through a percentage of body mass. Unlike the passive towing test in which the added-mass effect is negligible, during real-world conditions glide velocity never stays constant and we have a deceleration throughout this phase.

Hence the added mass becomes important and contributes to performance in conjunction with the resistive force that hinders performance. Additionally, a point of contact to the towing wire at the swimmer's hands or waist during passive towing may affect posture and alignment of the body. Changes in posture and body shape characteristics can affect the path of fluid flow and subsequent hydrodynamic resistance. For example, changes in head position from head up and head-down in an otherwise streamlined position reduced drag by 4-5.2% (Cortesi & Gatta, 2015). Other small postural changes in the streamlined body have been found to alter hydrodynamic resistance by up to 10% (Vennell et al., 2006). Nevertheless, passive towing may be effective for assessing consequences of broad anthropometrics changes in the morphology over a competitive season (Barbosa et al., 2015b), talent potential, and the effects of apparel design on drag (Webb et al., 2015).

Phases of deceleration in swimming are useful for determining hydrodynamic resistance of the body, as the net force is equal to hydrodynamic resistance in the absence of propulsive swimming actions. During the period when there are no propulsive actions, for example in the glide phase of breaststroke, or during a 'catch up' period in front crawl swimming without kicking, kinematic analysis may be used to assess the deceleration and compute measures of hydrodynamic resistance based on principles of inverse dynamics. These methods are advantageous for determining passive drag of swimmers as the effect of body inertia is considered, compared with other experimental methods of estimating passive drag. These experimental procedures allow swimmers to perform in an unconstrained manner resembling real swimming situations, for example in the glide (Thow et al., 2012). Therefore, kinematic analysis methods can enable assessment of the effect of technique and postures on hydrodynamic resistance.

Limitations of video-based analysis procedures ought to be considered when deriving kinematic measures of passive drag. For instance, accuracy of estimating glide distance from the velocity-time curve (Starling et al., 1995) is reliant on the derived initial velocity value from the video data, which is dependent upon camera specifications and susceptibility to propagation of digitising error when deriving velocity data. The Hydro-Kinematic method was developed to improve accuracy of passive drag analysis by calculating glide efficiency (glide factor) and initial velocity using a curve fitting mathematical operation (Naemi & Sanders, 2008). Because the function is fitted to the whole data set, errors normally associated with differentiation are avoided while also avoiding the constraints on posture associated with direct velocity measurement techniques in which the velocity of a fine cable attached to the swimmer is measured. Kinematic analysis methods, however, can be reliant on time consuming tracking operations of video data, such as manual digitisation. This problem may be overcome by using neural networks for automated digitisation of 2D glide video data. This has been shown recently to reduce data acquisition time without sacrificing accuracy in the derived glide variables (Papic et al., 2020). Automated video-tracking procedures can be implemented in applied settings to expedite glide efficiency outcomes using the Hydro-Kinematic Method to evaluate the effect of technique and posture on drag during swimming deceleration phases (start, turn, breaststroke). This approach can be used to provide quantitative performance feedback to swimmers and coaches when seeking to minimise drag (Papic et al., 2021; Thow et al., 2012)

Utility and limitations of active drag methods

Analysis of active drag force using the VPM (Kolmogorov & Duplishcheva, 1992), the ATM (Alcock & Mason, 2007) and the NABA method (Webb et al., 2011) enable determination of hydrodynamic resistance during maximal velocity free-swimming and all assume equal power conditions. Alternatively, the MAD-System (Hollander et al., 1986), HRM (Kolmogorov, 2008) and MRT method (Takagi et al., 1999; Narita et al., 2017) enable hydrodynamic resistance to be determined at a wide range of velocities. Furthermore, the HRM and the MRT methods can be used to assess active drag in any strokes without limiting the locomotion type (kick-only, arm-only, or whole-body), whereas the MAD-System method can be used only for front crawl arm-only swimming. Active drag methods can be used to assess the effect of anthropometric and morphological characteristics, and the effect of swimsuits and stroke technique on hydrodynamic resistance during active swimming conditions. However, specific limitations to evaluating each of these factors ought to be considered by researchers when selecting an appropriate method.

Some authors have demonstrated that active drag might be approximately 1.5 times greater than passive drag (Gatta et al., 2015), whilst others found it two or more times higher (Clarys, 1978, 1979;

di Prampero et al., 1974; Takagi et al., 1999; van der Vaart et al., 1987) and, finally, other studies concluded that both provide similar results (Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Toussaint et al., 1988). Indeed, inconsistencies in estimated drag force values exist when comparing each active drag method. Active drag values using the MAD-System were 55% less ($p = 0.002$) than those calculated using the ATM (Formosa et al., 2012). The ATM was found to produce greater active drag values than the VPM (Mason et al., 2013) and the NABA showed similar results to VPM at supramaximal velocities (Webb et al., 2011). The MAD-System also revealed significantly greater mean active drag values (66.9N) than the VPM (53.2N) (Toussaint et al., 2004). The MRT method was found to have greater active drag values than the MAD-System (Narita et al., 2018a). For the HRM method there are no direct comparisons with other solutions, but published data point to higher values (~80 to 90 N for front crawl Olympic champions). Differences between active drag experimental methods may be due to different technique and postural manipulations, as well as to the theoretical assumptions imposed when estimating hydrodynamic resistance. As the eminent physicist Carlo Rovelli stated in his remarkable book "L'ordine del tempo" (Milano, Adelphi Edizione, 2017), "assessing a physical variable is not an innocuous operation: it is interacting"; consequently, further research is needed to clarify this apparent cascade of active drag inflation: from VPM and NABA to HRM, passing successively through the MAD-System, ATM and MRT.

The MAD-System requires swimmers to contact underwater pads at set distances, which may promote anticipatory movements and alter natural stroke length and mechanics (Sacilotto et al., 2014). Despite the evidence on EMG similarity between MAD swimming and free front crawl (Clarys et al., 1988), the hand contact with a rigid object in the MAD-System may also alter regular stroke mechanics, compared with displacing water during regular stroke cycles. As Narita et al. (2018a) hypothesised, the propulsive force generation is likely more efficient when in contact with fixed pads than when the hand moves through water. Additionally, the use of a pull buoy during MAD-System data collection eliminates the effect of kicking on axial rotation of the body (Andersen & Sanders, 2018; Yanai, 2001) and, consequently, the potentially beneficial or adverse effects on hydrodynamic resistance.

The VPM, NABA, ATM and MRT methods all involve physical attachment of a cable to the waist of a swimmer. Assistive or resistive forces at the waist may alter posture and alignment of the hips and lower limbs with respect to the thorax, influencing the angle of the trunk. The angle of the trunk with respect to the external horizontal axis - trunk incline -, affects hydrodynamic drag (Zamparo et al., 2009). Postural effects on active drag force can also be detected when comparing different swimming strokes with similar transverse cross-sectional area. Gonjo et al. (2020) reported that the mean underwater body volume during one stroke cycle is greater in backstroke than in front crawl by 3.5-4.5%, and active drag is also 25% greater in backstroke at the same velocity (1.2 m/s). It was hypothesised that differences in posture and upper limb kinematics between the two strokes affect underwater body volume, and consequently, hydrodynamic resistance (Gonjo et al., 2020).

A limitation of some methods of active drag analysis, as in the MAD-System, is the assumption that the swimming velocity is constant and therefore the mean active drag is equal to the mean propulsive force. In fact, swimming velocity within a stroke cycle is not constant and so drag force is not constant throughout the cycle. This problem is amplified when one considers that the relationship between drag force and velocity is not linear and so the average velocity cannot be expected to be accurately related to the average force. The more recent methods, however, seem to avoid this issue, allowing for considering intracyclic speed variations. Furthermore, planimetric frontal surface area (FSA) calculation on land (Toussaint et al., 1988) or by numerical estimation (Kjendlie & Stallman, 2008) has been used for drag calculations in most methods. HRM and MRT methods seem to be exceptions. A recent study investigated the effect of FSA and velocity variation on active drag, at key events during the front crawl stroke cycle (Morais et al., 2020). Morais et al. (2020) found that active drag values were greater when using instantaneous measures of FSA and velocity throughout the stroke cycle, than when applying the common non-variation assumption. This finding is critical to our understanding of the effect of body shape on hydrodynamic resistance, as postural changes in free-swimming influence the magnitude of hydrodynamic resistance.

Implications for free-swimming technique analysis

Numerous studies have been conducted with the aim of improving swimming technique either through kinematic analysis, intervention studies, or kinetic analysis. Although research into accurately measuring kinetic variables in free-swimming is still in its infancy, investigations have progressed from investigating active drag utilising mean values (Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Sacilotto et al., 2012). In recent years increased attention has been accorded to generating active drag force-time profiles with the aim of utilising them as objective assessments of free-swimming performance (Kolmogorov, 2008; Mason et al., 2013; Sacilotto et al., 2013; Sacilotto et al., 2015). Sacilotto et al. (2014) attempted to use correlations between coach ratings of technique and ATM force-time profiles. However, between-coach ratings of technique were inconsistent, and therefore, no inferences could be drawn from the profiles. Further attempts were made using the ATM to successfully group elite and sub-elite swimmers by only their force-time profiles utilising functional components analysis (Sacilotto et al., 2015). The ATM force-time profiles enabled identification of elite and sub-elite groups as it was revealed that the elite group has a more pronounced positive double peak profile than the sub-elite, however, future work investigating technique analysis should focus on determining what technique attributes result in these double peaks (Sacilotto et al., 2015).

Morais et al. (2020) compared active drag calculations between a single frontal surface area land-based measure (non-variation) versus using frontal surface area measures obtained at key-events during the stroke cycle of front-crawl swimming (variation) and compared mechanical power variables computed based on these two approaches. Active drag based on a variation approach was measured in each key event of the front crawl according to the law of linear motion. The output data suggested that frontal surface area and velocity changed during the front-crawl arm-pull. This variation had a significant effect on the active drag, mechanical power, and total power input variables measurement. This resulted in higher values in a variation approach than a non-variation approach, due to frontal surface area being higher in a variation condition in specific phases of the stroke cycle. Hence, researchers and practitioners should be aware that there could be considerable error when measuring such variables based on an assumption of non-variation of the frontal surface area and velocity, and wherever possible should consider selecting methods that include instantaneous measures of these outcomes.

Conclusion

This review provides readers and researchers with a range of opportunities and considerations when conducting future research in active and passive drag in relation to athlete morphology, apparel, and technique analysis. Passive towing drag assessments may be of high relevance for training due to its relationship with gliding, morphology, and apparel influence, as well as with active drag. Nevertheless, inverse dynamics solutions may be preferable as these could applied directly to provide feedback on technique. Results provided by different active drag assessment methods are inconsistent, particularly when compared to passive drag. However, direct comparisons are scarce and require future attention. Some of the methods are limited to maximal velocity analysis, or to mean cycle results, and others are limited to front crawl arm swimming alone. Finally, some methods allow for intracycle variation analysis, which can be used to provide technical feedback and specific morphologic and apparel effects analyses. However, future research is required to guarantee robustness, validity, and reliability. As a guide, researchers should continue to consider the accessibility, feasibility, and limitations of using each method outlined in this review. We recommend researchers select a method that closely matches their research question and the phase or swimming task for the greatest translatability of findings to competitive free-swimming.

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