Hydrodynamic glide efficiency in swimming

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Abstract

The glide is a major part of starts, turns and the stroke cycle in breaststroke. Glide performance, indicated by the average velocity, can be improved by increasing the glide efficiency, that is, the ability of the body to minimise deceleration. This paper reviews the factors that affect glide efficiency. In the first part of the review the sources of resistive force are reviewed including surface friction (skin drag), pressure (form) drag and resistance due to making waves (wave drag). The effect of body surface characteristics on the skin drag, the effect of the depth of the swimmer on wave drag, and the effects of posture and alignment, body size and shape on the form drag are reviewed. The effects of these variables on the added mass, that is, the mass of water entrained with the body are explained. The ‘glide factor’ as a measure of glide efficiency that takes into account the combined effect of the resistive force and the added mass is described. In the second part methods of quantifying the resistive force are reviewed. Finally, the ‘hydro-kinematic method’ of measuring glide efficiency is evaluated.

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1. Introduction

The ‘glide’ refers to phases in swimming races during which the swimmer attempts to maintain speed without actions to propel the body. Glide phases occur during starts, turns, and within stroke cycles of breaststroke. During the glide phases of starts and turns swimmers typically adopt a ‘streamlined’ position characterised by an elongated posture with arms extended forward with hands pronated and overlapping, and the feet together and plantar flexed. Maintaining a passive streamlined posture during the underwater period of starts and turns is beneficial when the body’s velocity is higher than that which can be sustained by kicking.1

Average velocity over the period of the glide is an indicator of glide performance. It depends on the initial velocity, the magnitude of deceleration, and the glide duration. Initial velocity of the glide is related to the preceding actions and is affected by characteristics of the pre-glide phase including entry after the start, or the push-off force and body position during wall contact in turns. According to Newton’s second law of motion, the deceleration during a glide depends on the resistive forces applied to a body and its inertial properties.

The resistive forces act opposite to the direction of travel and their magnitude is highly related to velocity. Inertia of a gliding body is the sum of the body mass plus the mass of water entrained with the body. This mass of entrained water, referred to as ‘added mass’, adds to the inertia and therefore reduces the rate of slowing of a gliding body. This mass of entrained water, referred to as ‘added mass’, adds to the
inertia and therefore reduces the rate of acceleration of the body during the propulsive phases and can in this respect be a negative factor in the preceding actions such as a push from the wall during a turn. But the added mass reduces the rate of slowing of the body during the glide when only resistive forces are acting and the body is decelerating. The inertia of a gliding body, being the sum of body mass and the added mass, is termed its ‘virtual mass’.

Glide efficiency can be defined as the ability of a gliding body to maintain its velocity through time and to minimise deceleration at each corresponding velocity. The lower the resistive force and the higher the virtual mass, the lower the deceleration at each corresponding velocity and thus the higher the glide efficiency. Although increasing initial velocity of a glide is one of the ways to optimise the glide performance, improving glide efficiency can be beneficial because an advantage is gained without increasing the metabolic cost.

Factors that affect glide efficiency include posture, alignment, and anthropometric and morphological characteristics of the body. These factors are explored in the first part of this review. The methods of measuring glide efficiency and the factors that affect glide efficiency are reviewed in the second part of the review.

2. Part 1: factors affecting glide efficiency

To have a better understanding of the hydrodynamic factors contributing to the glide efficiency, knowledge of different types of flow and their characteristics is essential. Two distinct conditions of flow around a body are referred to as ‘laminar’ and ‘turbulent’ flow. Laminar flow is characterised by smooth motion in of fluid in ‘layers’. The turbulent flow is characterised by the random three-dimensional motion of the fluid particles superimposed on the mean motion.

Whether the flow acting on a body is considered laminar or turbulent can be determined by the Reynolds number which defines the magnitude of the inertial to the viscous forces on the flow particles acting on a body. This can be calculated by

$$Re = \frac{\rho v L}{\mu}$$

where $\rho$ is the fluid density, $v$ is the body’s velocity, $L$ is the characteristic length of the object in the direction of the flow and $\mu$ represents a constant known as ‘viscosity’.

For a smooth flat plate with no surface irregularities, the transition from a laminar to a turbulent flow occurs at Reynolds numbers of $5 \times 10^5$. Assuming that the transition occurs at the same Reynolds number, if not lower, for the human body in a streamlined position, at a velocity of about 2.5 m/s which is common during the glide phase of starts and turns, only about 20 cm of the body length, that is only the hands, remains in a laminar flow. ‘Skin roughness’ which depends on the height and shape of irregularities on the surface, influences the amount of random motion of the fluid particles, causing the transition to occur even earlier for glides under real conditions. Transition occurs at even lower Reynolds numbers in decelerating flow, as is the case for gliding bodies, than for bodies moving with a constant velocity. Thus it can be concluded that for the ranges of Reynolds number corresponding to glides of the human body in competitive swimming, turbulent flow is dominant along almost the whole length of the swimmer.

The resistive force, otherwise known as ‘drag’ acts opposite to the direction of motion of the body and is highly related to the flow conditions and the body characteristics. The term ‘passive drag’ refers to the hydrodynamic resistive force acting on a body that is not actively changing the orientation of the body segments, that is, on a body during a glide. The motion of a body travelling through water close to the surface is affected by ‘friction’; ‘pressure’ and ‘wave making’ resistance. Alternative terms are ‘skin drag’, ‘form drag’, and ‘wave drag’ respectively.

Frictional resistance or ‘skin drag’ is the contribution to the drag that exists due to the presence of a ‘boundary layer’. According to the boundary layer theory the flow around a body is divided into two regions, one close to the body surface and the other covering the volume beyond the region close to the body surface. The boundary layer is defined as that part of the flow adjacent to the body in which the effect of viscosity is important. In this area the flow velocity at the surface of the body is considered to be zero due to no-slip conditions. At increasing distances from the body surface the flow velocity increases until it reaches the ‘free-stream’ velocity. The free-stream velocity is expressed relative to the moving body. In the case of a body gliding in a swimming pool in which the water is initially stationary, the free-stream velocity can be regarded as the velocity of the swimmer. The location at which this occurs is known as the ‘boundary layer border’. Beyond this border, the flow is regarded as without friction since the velocities of different layers of the flow are the same.

Decreasing roughness to create a smoother surface decreases the amount of the frictional resistance for a gliding body. Latex swimming caps and body shaving are believed to reduce the friction drag by decreasing the surface roughness. Quantifying the contribution of the frictional drag to total drag has been extremely difficult. Recently, using Computational Fluid Dynamics analyses (explained later in the manuscript under the same heading) of a human body in a streamlined position at constant velocities, Bixler et al. found that the skin friction corresponds to about one fourth of the total drag when the swimmer is submerged to a depth where wave drag is negligible. The remaining drag is the result of pressure drag. In that study surface roughness was regarded as zero. For a real swimmer with some surface roughness the contribution of frictional drag to total drag may increase.

Pressure drag is the result of the differences between pressure at the leading and trailing edges of the body. Moving along the body, the fluid particles in the boundary layer are
slowed down by the wall shear stress as a result of the skin friction. When the momentum of the fluid in the boundary layer is insufficient, the flow cannot follow the curve of the body and separates from the surface. Boundary layer separation results in formation of a relatively low-pressure region behind the body.\(^4\) This region, which is deficient in momentum, is called ‘wake’ although wake is not necessarily the product of separation.\(^8\) Separation of the flow from the body leads to the formation of large and small eddies at the downstream part of the body resulting in form drag\(^3\) because the eddies exert less pressure on the body than the water in the upstream sections that has not yet separated from the body.

Form drag is created as a result of the pressure difference between the leading and trailing edges of the body. The form drag is equal to the amount of this pressure difference times the area to which the pressure is applied. Thus in addition to the effect of flow separation on drag increasing the projected area to the flow increases the pressure drag. Numerous studies revealed that certain actions like having the head above the water, turning the head to breathe, lowering the legs, having legs and arms abducted and body rolling during the streamlined glide on the surface would increase the total drag forces mainly due to an increase in the projected area.\(^9–11\) During these actions parts of the body protrude beyond the maximum cross-sectional area of the chest thereby increasing the projected area and consequently the pressure drag. An increase in the ‘angle of attack’, that is, the angle of the body to the direction of flow, can also result in an increase in the projected area. Using CFD analyses Bixler et al.\(^7\) found that angles of attack of \(3^\circ\) and \(-4.5^\circ\) increased the total drag by 2.3% and 2.4% respectively compared to a zero angle of attack.

Because of the effect of chest cross-sectional area on the pressure drag some anthropometric parameters like the chest girth, depth and breadth have been found to be significantly correlated with drag values.\(^12–14\) In addition to the anthropometric parameters, the shape and the contour of body are important factors affecting the pressure drag because they determine how the flow moves over the body. For example, the bodies of aquatic mammals are contoured so that the flow particles remain in laminar streams without separating from the body until near the trailing edge of the body.\(^15\) In contrast the shape of the human body causes early separation and the flow is turbulent rather than laminar along most of its length. Consequently the drag of a human in its most streamlined position is approximately five times the drag for a submerged seal with the same weight at a comparable depth.

Counter-intuitively, turbulence may be produced deliberately to delay separation and reduce drag. Dimples on a golf ball are a particularly well-known example. The dimples produce turbulence in the layer closest to the ball, that is, the boundary layer. Having a higher momentum, a turbulent boundary layer is more resistant to separation. Recently ‘turbulators’ and ‘turbulence amplifiers’ have been designed by some swimsuit manufacturers to increase the turbulence in the boundary layer to delay or minimise separation to reduce drag. Despite these no factual research has been released by these companies.

Another way of delaying separation is to mix the high speed free-stream flow with the low-speed flow in the boundary layer. This increases the momentum at the near wall region to reduce flow separation and consequently the pressure drag. ‘Vortex generators’ have been installed on swimsuits upstream of the areas where large separations and turbulence tend to occur. Testing of human replicas in a wind tunnel has indicated that these can decrease resistance.\(^17\) However, independent testing in water in conditions resembling actual glides of swimmers is required.

Like frictional resistance, pressure resistance is hard to quantify experimentally. CFD analyses revealed that pressure resistance corresponds to about 75% of the total drag of a submerged swimmer in a streamlined position at velocities between 1.5 and 2.25 m/s and at depths where wave making resistance was negligible.\(^7\) The contribution of pressure resistance to total drag would be less than 75% when wave making resistance is present.

Wave making resistance or wave drag acts on a body when moving close to the surface. Part of the energy from the moving body is used to lift the water against gravity resulting in the formation of waves on the surface.\(^18\)

The wave drag is highly related to a Froude number (Fr) that determines the ratio of inertial to gravitational forces applied to fluid particles. This dimensionless ratio can be quantified as:

\[
Fr = \frac{v}{\sqrt{L \cdot g}}
\]  

where \(v\) is the velocity of the moving body, \(L\) is the length of the body in direction of flow and \(g\) is the gravitational acceleration constant. It is believed that the wave drag increases with the Froude number. Extending the arms forward increases the body length and thereby reduces the Froude number and consequently the wave drag compared to a posture in which the arms are against the body. For example it was reported that having arms on side results in 21.5% more drag compared to the streamlined position.\(^18\)

The Froude number can be used to indicate a limiting velocity for a swimmer gliding on the surface. At the Froude number of 0.45 where the swimmer with an extended height of 2.5 m reaches the hull speed of 2.23 m/s the wave length is equal to the extended height of the swimmer.\(^20\) As the swimmer is unlikely to hydroplane this can be considered as a limiting factor for a swimmer gliding on the surface. In addition to the excess effect of wave drag on the surface, the limitation in the maximum achievable speed is another limiting factor preventing swimmers to glide on the surface after starts and turns.

Wave drag is also dependent on the depth at which the body travels.\(^19\) At a depth of three times the body thickness the wave drag becomes negligible, and has its maximum value when it is submerged just beneath the surface. Recently, Lyttle et al.\(^13\) and Vennell et al.\(^20\) established that the wave drag is...
negligible at a depth of about 0.6 m underwater. It was found that at a velocity of 2.5 m/s on the surface the wave drag contributes to at least 40% of the total resistance, while at 2 m/s and at a depth of 0.4 m the wave drag corresponds to only 15% of the total drag. Therefore, in the glide phases of starts and turns, swimmers should glide at sufficient depth to minimise the effect of the wave drag.

The sum of different types of resistance, ‘total drag’, can be estimated by the following formula:

\[ D_d = \frac{1}{2} c_d \rho A v^2 \]  

\( D_d \) represents the total hydrodynamic resistance, \( \rho \) is the water density, \( v \) is the velocity of the body and \( A \) is the reference area. In the case of humans, because of the dominance of pressure drag compared to other types of drag for a submerged body at an adequate depth, the projected area replaces the reference area in the total drag formulae. When the body is well aligned to the flow with zero angle of attack the projected area has its minimum value equal to the maximum cross-sectional area of the body.

The dimensionless drag coefficient \( (c_d) \) indicates the level of ‘streamlining’. It is an empirical constant dependent on the body shape, angle of attack, surface roughness and the flow characteristics. \( c_d \) has been reported to be between 0.65 and 0.75 for a swimmer in their most streamlined position at the surface, while the drag coefficient of a submerged human body at an adequate depth was found to be about 0.30. Recently Vennell et al. found that the drag coefficient varies with velocity, a fact that is not traditionally considered in swimming research.

It is also highly popular in the swimming literature to report a resistive factor as the ratio of total drag force \( (D_d) \) to the velocity squared. A resistive factor \( (C_R) \) in kg/m incorporates the maximum cross-sectional area \( (A) \), the fluid density \( (\rho) \), and the dimensionless drag coefficient \( (c_d) \) according to the following formula:

\[ C_R = \frac{1}{2} c_d \rho A \]  

The resistance to change in motion of a body is its ‘inertia’. Thus, a gliding body tends to keep moving without any changes in the velocity while the resistance is acting to slow it down. In a vacuum the only source of inertia is the mass of the body, while in the presence of a fluid a quantity of the fluid around the body, not only does the mass of body need accelerating (or decelerating) so does some of the adjacent fluid. Thus the apparent (virtual) mass that resists acceleration is larger than the physical (body) mass. During a glide, the inertia is the sum of the mass of the swimmer and the added mass of water. This sum is called ‘virtual mass’.

The added mass represents the particles of fluid adjacent to the body that move with the body to varying degrees, depending on their position relative to the body. In principle every fluid particle would accelerate to some extent as the body moves, and the added mass is the weighted integration of this entire mass. It can be argued that the added mass is a result of the same phenomena that contribute to the resistive forces, these being the boundary layer, the flow separation and the presence of waves at the surface.

The mass of fluid in the boundary layer presents a source of added mass. When the fluid is stationary and the body is moving due to no slip conditions at the body surface (as was explained under skin friction), the fluid particles at the surface of the body move with the same velocity as the body, while outside the boundary layer the fluid particles stay still. In the boundary layer, shear stress causes the different layers of fluid to move with speeds that decrease with increasing distance from the body surface. The moving water represents a source of added mass in the areas of attached flow. The amount of the added mass then depends on the thickness of the boundary layer and the relative velocity distribution of the flow in the boundary layer. A simplifying assumption is that a fraction of the boundary layer moves with the same speed as the body and the remaining part stays still. The thickness of that fraction depends on the viscosity of the fluid. The velocity of flow and thickness of the boundary layer can be determined using methods that allow flow visualisation such as CFD. However, there is a paucity of data regarding the added mass of gliding human bodies.

Another source of added mass is a result of the wake formation. In the areas of flow separation a wake forms in which the velocity of the fluid particles relative to the body is zero. During deceleration this bulk of fluid is decelerated at the same rate as the body and acts as an added inertia.

Added mass increases when a swimmer is gliding close to the surface. The waves created by a swimmer move at the same velocity as the body and act as a source of added mass. These include the wave formed at the leading edge of the swimmer, the ‘bow wave’, as well as the waves formed at the trailing edge, ‘stern wave’.

The total added mass is the sum of the added masses according to the contributions of all sources. When a dimensionless added mass coefficient \( (ca) \) is defined as the ratio of the accelerated mass to displaced mass of the fluid by the body, then the added mass can be written according to the following formula:

\[ m_a = c_a \rho V \]  

where \( m_a \) is the added mass, \( \rho \) is the density of water, and \( V \) is the body volume. Determining added mass coefficient requires details of the geometry and physics of the flow, and was determined for certain geometries in a frictionless fluid. Because of the irregular shape of a human body there is no information available on the amount of added mass for deceleration during a glide.

Like the drag coefficient the added mass coefficient decreases with improvement in streamlining. For a por-
poise the added mass coefficient is about 0.045.\textsuperscript{24} For a human body it can be speculated that in a fixed position and depth the added mass coefficient may vary across velocities. This can be attributed to the fact that changes in velocity would result in changes in the boundary layer thickness and variations in the wake volume. Since the wake and boundary layer are the sources of added mass at adequate depth, depending on the extent at which the changes in velocity affect the amount of added mass from these two sources, the added mass coefficient may vary across velocities.

The more streamlined a body the less the added mass. By adopting a streamlined position and gliding at an adequate depth, the swimmer decreases the size of the wake and the amount of wave entrained. This results in a decrease in the added mass. Although it may seem that the reduction in the added mass may be detrimental for glide efficiency, the overall effect is beneficial. As the added mass makes a small proportion of the virtual mass, an equal decrease in the drag and added mass coefficient will result in an increase in the glide efficiency. This can be seen in Eq. (7) in the following section.

The hydrodynamic parameters of a body including the resistive and inertial characteristics change with modifications in the body position during a glide. Thus in determining the effect of different factors on the glide efficiency, the resistive and inertial parameters should be considered in conjunction with each other. Contrary to the resistive force that can be determined by the conventional methods (which are going to be explored in the second part of the review) the added mass cannot be quantified easily. Recently Naemi and Sanders\textsuperscript{2} introduced a ‘glide factor’ as a holistic measure of glide efficiency that takes into account the combined effect of both the resistive and inertial parameters.

Naemi and Sanders\textsuperscript{2} argued that based on the equation of motion of a representative body during a glide (Eq. (6)), at each corresponding velocity, the higher the virtual mass and the lower the resistive factor the less the body decelerates, leading to a higher glide efficiency.

\[ M \frac{dv_x}{dt} = -C_R v_x^2 \]  \hspace{1cm} (6)

Using Eq. (6) Naemi and Sanders\textsuperscript{2} proposed that the ratio of velocity squared to deceleration can be used as a measure of glide efficiency. This ratio is called glide factor by Naemi and Sanders\textsuperscript{2} denoting the ratio of virtual mass to the resistive factor from a hydrodynamic point of view (according to Eq. (6)).

Thus a glide factor was introduced by Naemi and Sanders\textsuperscript{2} as the ratio of virtual mass (\( M \)) to the resistive factor (\( C_R \)) (Eq. (7)) that indicates the ability of a body to minimise deceleration at each corresponding velocity.\textsuperscript{2}

\[ C_G = \frac{v_x^2}{-a_x} = \frac{M}{C_R} = \frac{m + c_m \rho V}{1/2(A \rho c_d)} \]  \hspace{1cm} (7)

The glide factor (\( C_G \)) in meter can be quantified with a hydro-kinematic method (reviewed at the end of the second part) without the need to know the resistive factor or the added mass separately.

Naemi and Sanders\textsuperscript{2} showed that the effects of size and shape on the glide efficiency can be distinguished by considering the glide factor as the product of a size-related glide constant and a shape-related glide coefficient. This was achieved by replacing the virtual mass as the product of dimensionless virtual mass coefficient (\( c_m \)); affected by the body shape; and the body mass (\( m \)) and rewriting Eq. (7) as follows:

\[ C_G = \frac{m}{1/2(A \rho)} \frac{c_m}{c_d} \]  \hspace{1cm} (8)

Naemi and Sanders\textsuperscript{2} defined the first term on the right side of Eq. (8) that incorporates the known constant parameters including the body mass (\( m \)), the maximum cross-sectional area (\( A \)) and the water density (\( \rho \)), as the glide constant (\( \lambda \)) in meter:

\[ \lambda = \frac{m}{1/2(A \rho)} \]  \hspace{1cm} (9)

The ratio of the virtual mass coefficient (\( c_m \)) to the drag coefficient (\( c_d \)) (second term in the right side of Eq. (8)) was defined by Naemi and Sanders\textsuperscript{2} as a dimensionless glide coefficient (\( c_g \)).

\[ c_g = \frac{c_m}{c_d} \]  \hspace{1cm} (10)

The glide coefficient was used by Naemi and Sanders\textsuperscript{2} to determine the shape-related glide efficiency for each swimmer independent of body size. According to this the glide factor is the product of the glide constant and the glide coefficient, while the former is influenced by the body size, the latter is affected by the shape characteristics of a body in a streamlined position.

In the second part of the review the methods of determining the resistive force and the glide efficiency are explored.

\section*{3. Part 2: methods of determining hydrodynamic parameters}

The total drag can be quantified either by directly measuring the force or by calculating drag based on the kinematics of a gliding body.

The force can be measured directly while a body is being towed in still water or exposed to a flow at a constant velocity. The total drag force is equal to the towing or holding force.

Forces can be measured during towing using either stationary or moving apparatus. In the stationary apparatus a cable on a rotating winch on the waterside pulls the body through still water. The towing force is equivalent to the drag force and is measured at different constant velocities and the
force would be measured directly by a strain gauge or load cell.9,12,25

In the moving apparatus the swimmer is attached to the carriage via a telescopic rod to which a force transducer is attached.26 This type of apparatus was used in a number of different studies in 70 s.27–29 In order to collect force data over a longer period of time, the moving apparatus can be used continuously over a circular path.30

Drag measurement in a fixed position requires exposing the body to fluid moving in a flume and measuring the force required to hold it in the flow.10,11,31 To increase the accuracy of the drag force measurements the free-stream turbulence and the wave created by the flume current should be controlled.32 Further, attachments to the swimmer may affect the posture and comfort of the swimmer. To overcome these problems, Vennell et al.20 used model replicas of swimmers fixed with a specifically designed towing rod in a sophisticated flume enable of producing even current at predetermined velocity across the whole testing area. This enabled testing the model at a consistent posture at different velocities and depths. Bixler et al. found that the results show about 18% more drag for a live subject than for a model.7 This may result from the non-compliant nature of the mannequin’s body surface.

‘Numerical simulations’ involving solving the Navier–Stokes differential equations that govern the equation of motion of the fluid particles is a relatively new approach that provides the advantages like the ability to visualise the entire flow domain and can distinguish between the different sources of resistance including the pressure and friction drag. Bixler et al. used such a technique to calculate the drag forces on a virtual body model based on a scan of a human body. Conducting steady state analyses at different velocities the resistive forces were found to be within 4% of the drag values of the mannequin replica measured in a flume. The discrepancies between the CFD results and the drag forces on a live subject might be related to the possible differences in the level of skin roughness and upstream turbulence in the model and in reality.33 The disadvantage of CFD can be seen as the inability to model the compliant surface of a body using software designed to model flow over solid bodies.

The total drag force applied to a body during a glide is equal to the deceleration multiplied by its inertia. Klauck and Daniel solved the differential equations of motion of a gliding body to model the velocity as a hyperbolic function of time. The ‘resistive factor’ was determined by fitting a hyperbolic velocity function to the measured instantaneous velocity–time data. The added mass was not considered and the body mass was assumed to be equal to the virtual mass leading to underestimation of the drag forces compared to those obtained during the towing experiments at the constant velocities.34 This re-emphasises the need for considering the added mass as an important part of the inertia.35

The added mass of aquatic animals can be approximated by assuming that they resemble bodies of revolution.36 Due to the irregularity of the human morphology the added mass of a human body cannot be approximated by these methods.

To quantify glide efficiency the distance travelled during glide intervals of identical initial velocities have been measured by calculating the area below the velocity–time curve during the glides after maximum push-offs from the wall.37 Since the initial velocities were calculated based on the position data in two frames, the initial velocity values may not represent a reliable method of selecting two glide intervals for comparison. Sharp and Costill38 used regression analysis to determine an exponential decay rate constant of the velocity when the velocity drops from 2 to 1 m/s. Using regression analysis38 provides more accurate results by fitting a curve to a number of data points over the whole period of glide compared to the method used by Starling et al.37

Despite this, the exponential velocity decay rate does not provide an insight into the resistive or inertial parameters of body. Naemi and Sanders in 2004 (as cited in Ref. [2]) established that a hyperbolic function which assumes that drag is proportional to velocity squared (Eq. (6)) provides a better fit to the raw velocity data than an exponential function that assumes drag to be proportional to velocity. Unlike the exponential fit, when a hyperbolic parametric curve is fitted to the velocity data of a glide, a parameter can be deduced from the curve that has an identity in terms of the hydrodynamic function.2 Despite the fact that a measure of the glide efficiency can be extracted by fitting a hyperbolic function (as a parametric fit) to the velocity data, Naemi and Sanders2 reported fluctuations in velocity data that could affect the accuracy of the obtained values.

To relate the hydrodynamic characteristics of a human body in a streamlined position including resistive and inertial properties to the kinematics of glide, Naemi and Sanders2 proposed a method of quantifying glide efficiency using parametric curve fitting. In the method dubbed ‘hydro-kinematic method’ the displacement over time is fitted by a parametric equation (Eq. (11)) that is obtained by solving the differential equation of motion of a representative body during glide (Eq. (6)).2

\[
x = C_G \cdot \ln \left( \frac{V_i}{C_G} t + 1 \right)
\]

where \(V_i\) is the initial velocity and \(C_G\) is the glide factor. The parameters of the curve that provide the best fit to the displacement data gathered from video analyses determine the glide factor and the initial velocity. Naemi and Sanders2 provided an example of using a parametric curve fitting technique to fit the displacement function (Eq. (11)) to the displacement data of a body during a relatively short glide interval of about 0.4 s. The glide factor of 4.62 m and the initial velocity was 2.34 m/s, were the parameters of a curve that provided the best fit to the data with an R-squared value of 0.99. The glide factor is a measure of glide efficiency of the glide interval and corresponds to the average velocity of glide. For example, in this case an average velocity of 2.14 m/s...
can be calculated based on the distance travelled after 0.4 s (Eq. (11)). Repeating the same procedure for a number of glide intervals selected form underwater glide trials following static push-offs from the wall for each swimmer, Naemi and Sanders\(^2\) found a profile of glide factor versus average velocity for each swimmer, and reported a linear regression line with a distinctive intercept and gradient for each individual, that can be used to compare the glide efficiency between individuals across different velocities.

The advantage of the method is that fitting the displacement function to the displacement data, rather than fitting a velocity function to the derived velocity data, increases the accuracy of the calculation as the errors in the displacement data do not get amplified when deriving velocity. The method enables glide efficiency to be determined in realistic glide conditions and without the need to know the resistive and inertial parameters (virtual mass) as separate parameters. With this method, the effect of body surface characteristics, posture, body alignment and depth on the glide efficiency can be determined accurately and reliably.

Because the glide factor takes into account the inertial effect that includes both added mass and body mass it is a more valid and realistic measure of glide efficiency; defined as the ability of a body to maintain its velocity and minimise deceleration; than measures of the resistive force alone. For example, as larger and heavier swimmers experience large values of passive drag, it may be interpreted incorrectly that this type of swimmer decelerates faster during glides and may have a disadvantage compared to slim swimmers who encounter less drag. This interpretation ignores the fact that the heavier swimmers have higher inertia, which together with the resistive force affects their deceleration during a glide.\(^2\)

Naemi and Sanders\(^2\) found that the method was able to distinguish between swimmers in their glide efficiency, and reported the glide factor to vary between 2.7 and 4.8 m\(^{-1}\) (at average velocity of 2 m/s) for the individuals tested at their most consistent streamlined position. While the variations of the glide factor within individuals was much less than the variations between individuals, the former was related it to the differences in the body shape and size.\(^2\) Naemi and Sanders\(^2\) also found that the glide factor increases as the swimmer reaches the lower velocities during a glide. This is in line with the findings of Vennell et al.\(^20\) that indicate a lower drag coefficient, so a lower resistive factor, at the lower towing velocities.

The fact that the glide factor values, as the ratio of virtual mass to the resistive factor, are more than unit indicates that the virtual mass represents a larger value than the resistive factor. During the glide the only force that is applied to the body in horizontal direction is the drag force, at each instant during a glide the product of deceleration and the virtual mass is equal to the resistive factor times velocity squared (Eq. (6)). Thus the ratio of the virtual mass to the resistive factor is equal to the ratio of velocity squared to deceleration. This indicates that the higher the glide factor the higher the ratio of velocity squared to the deceleration, or a less deceleration at each velocity denoting higher glide efficiency.

By measuring the maximum cross-sectional area \((A)\) using a photogrammetric method and knowing mass of the swimmer Naemi and Sanders\(^2\) calculated the glide constant \((\lambda)\) for each swimmers and reported it as 1.80 ± 0.14 m for the females and 1.88 ± 0.08 m for the males. The glide constant was used to determine the body’s size suitability to glide efficiently. For example heavier swimmers with a lower maximum cross-sectional areas (i.e. tall and slim body types) that posses a higher glide constant have a better potential to glide in terms of their size compared to the swimmers with a lower body mass and a higher maximum cross-sectional area (i.e. short swimmers with broad chest) who posses a lower glide factor.\(^2\)

Naemi and Sanders (2008) reported a dimensionless glide coefficient \((c_G)\) that was obtained by dividing the glide factor \((CG)\) by the glide constant \((\lambda)\). The reported glide coefficient was 2.14 ± 0.35, indicating a dimensionless coefficient that reveals the potential of the body shape to glide more efficiently. It was also indicated that the shapes that are able to entrain a large quantity of water while minimising the drag can glide more efficiently.\(^2\) The glide coefficient as a dimensionless ratio provides a way of comparing swimmers with different body size in terms of their body shape including streamlining posture and alignment. Also the glide coefficient has practical applications in testing the swimming suits designed to improve performance it considers the ability to reduce the drag force in conjunction with the effect on the ability of a body to entrain the added masses of water.\(^2\)

When the curve fitting technique cannot be used, Naemi and Sanders\(^2\) provided a formula (Eq. (12)) to estimate the average glide factor when the initial velocity \((V_{x0})\), the final velocity \((V_x)\) and the duration \((T)\) of a glide interval are known.

\[
C_G = \frac{T}{(1/V_x) - (1/V_{x0})}
\]  \text{(12)}

Based on this Eq. (12) Naemi and Sanders\(^2\) reported an average glide factor of 4.19 m based on the reported average initial velocity (2.86 m/s), average glide duration (1 s) and the average final velocity (1.7 m/s) of five male participants reported by Lyttle.\(^13\) As the concept of glide efficiency and the way to measure it are new\(^2\), there has not been any previous literature to compare the results with what was reported by Naemi and Sanders.\(^2\)

4. Conclusion

- Inertial and resistive characteristics of a body in a streamlined position affect the glide efficiency.
- Most if not all the swimming research studies on the human body in streamlined position have focused on the resistive characteristics only. The effect of inertial factors, in particular, added mass, has received little attention.
• The conventional methods of the direct resistive force measurements may not represent the drag forces in realistic glide conditions, as the natural posture and flow characteristics around a swimmer’s body would be affected.

• Calculating drag based on the kinematics of the glide overcomes the deficiencies of the conventional direct force measurements by allowing the drag to be measured in a non-invasive way during more realistic gliding conditions. However, the results do not take into account the effect of added mass and the effect cannot be predicted.

• The hydro-kinematic method is a new method that can quantify the glide efficiency without the requirement of knowing the resistive and inertial parameters independently and promises huge benefits for the study of hydrodynamic characteristics of a human body during glide in future.

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References


