POLITECNICO DI TORINO

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Tesi di laurea

The Fluid Dynamics of Competitive Swimming

La fluidodinamica del nuoto competitivo

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1. Introduction

Competitive swimming is a fascinating and complex sport, whose main feature certainly is the interaction between the athlete and the surrounding medium, hence the importance of understanding - and, hopefully, controlling - its fluid dynamics, as a key to maximising performance and establishing new records. Starting from the studies of James "Doc" Counsilman, US Olympic swim coach, who in 1968 wrote the first modern science-based textbook on swimming [1], many scientists have focused their attention on this topic, trying to elaborate on the aspects that could, eventually, make the difference in a competition, as well as define the "perfect way" to swim. So, over the past few decades, several studies on thrust and drag [2][3], the role of the hand and the arm in the different styles [4][5], the 'dolphin kick' technique [6], the swimsuits [7] and many other features have been carried on, and a large variety of different approaches has been used, pointing out that competitive swimming represents a challenging advanced fluid dynamics problem, yet to be completely solved.

In this study, we will first introduce some fundamental definitions and the physical problem (Chapter 2), and then present various whole-body, experimental studies (Chapter 3) and numerical works (Chapter 4), which focus on the most important and interesting aspects of the fluid dynamics of competitive swimming. Furthermore, we will dilate upon the studies on two fascinating features, namely the wave drag and the 'dolphin kick' technique, from both the swimming and fluid dynamics points of view. Our aim is to provide a satisfactory knowledge of the main physical aspects related to competitive swimming, and, also, to show the evolution of this field of research from observation-based works to the integration of computational technologies into the sport.

2. Physical problem and preliminary definitions

In this chapter, we will introduce the physical quantities involved in the study of competitive swimming. We will first present a kinematical point of view, and then focus on the physical problem, also providing several fundamental definitions.

2.1 Key terms

Let us first define some key terms, commonly used in competitive swimming. Nowadays, this sport is divided into four major styles: front crawl, reverse crawl, butterfly and breaststroke. Front crawl and reverse crawl are also known as, respectively, 'freestyle' and 'backstroke'. The 'dolphin kick' consists of an undulating motion of the swimmer's body while underwater: FINA[1] regulations state that swimmers are allowed to do this only for the first 15 metres of each leg, except in breaststroke, where only one dolphin kick is permitted after each turn. The 'pull' refers to the part of the arm motion from the head towards the feet associated with propulsion. The 'catch' is the initial part of the pull, in which the athlete should catch as much water as possible to generate thrust. The stages that directly precede and follow the pull are also defined as 'transitions'. The 'recovery' is the phase of the arm motion in which the hand moves forward from the hip to the head, i.e. to the start of the next pull. The 'elbows up' position is a particular technique, performed at the beginning of the catch, whose goal is to get the forearms pointed straight down towards the bottom of the pool, in order to let the swimmer engage as much water as possible throughout the pull.

2.2 Kinematical perspective

The finishing clock is the only judge of athletes' performance during the race: therefore, the main goal of every competitive swimmer is to set the fastest time. For a start, this can be seen as a simple kinematical problem: the mean velocity (V) is the product of the stroke rate (S_r) and the distance moved through the water with each complete stroke (D_s),

$$V = S_r \times D_s$$

The greatest maximal V is achieved by maximising D_s, while swimming at slow S_r [8]: this condition is obtained by maximising thrust and, at the same time, minimising drag [9].

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[1] *Fédération Internationale de Natation (FINA)*

2.3 Physical problem

Therefore, competitive swimming can be studied by analysing the interaction between propulsive and resistive forces. The athlete is modelled as a body with certain shape and characteristics, fully or partially submerged in the water: these two different situations have significant relevance to the study, as the physical properties of the surrounding medium change above the water surface, bringing to different conditions: indeed, we will see that swimming near to the surface generates an additive resistance - namely, the wave drag. Whilst swimming, only hands and forearms, and sometimes legs and feet propel the athlete, while the other parts of the body generate resistance. A scheme of the forces involved in the problem, which are defined and briefly described below, is shown in Figures 1 and 2. We remind that physiology and energetics also play an important role in enhancing athletes' performance, but they fall beyond the scope of this research.

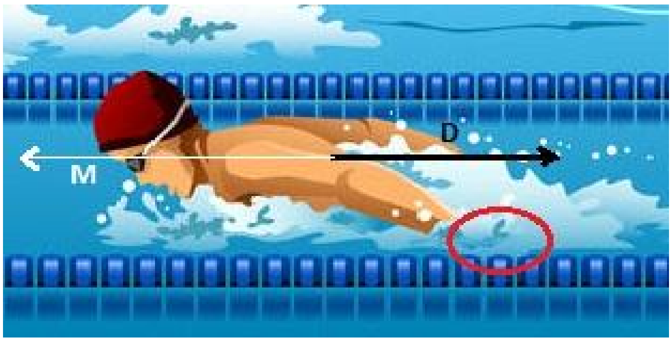

Figure 1. Hydrodynamic Drag

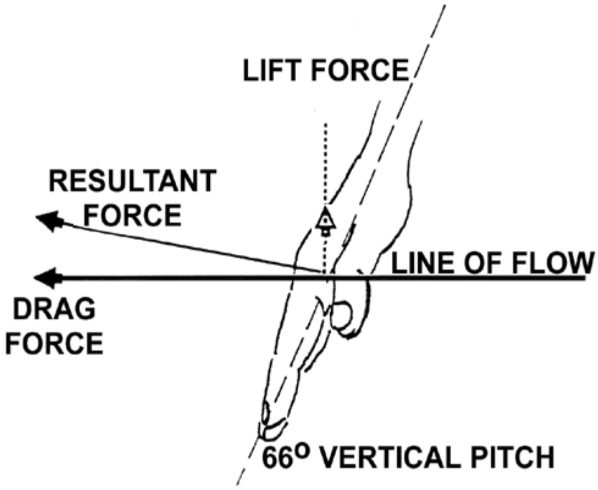

Figure 2. The components for assessing propulsive forces [10]

2.4 Hydrodynamic Drag

Let us first and foremost introduce the hydrodynamic drag (or hydrodynamic resistance), which can be defined as an external resistive force that acts in the swimmer's body parallel, in the opposite direction of his movement direction [11]. It depends on the anthropometric characteristics of the swimmer, on the characteristics of the equipments used by the swimmer, on the physical characteristics of the water field and on the swimming technique [12]. The hydrodynamic drag (D) can be expressed by the equation

$$D = c_D \frac{1}{2} \rho V^2 S$$

where ρ represents the fluid density, S is the projection surface of the swimmer, V is the swimmer's velocity and c_D represents the drag coefficient. In Figure 1, an example of total resistance in butterfly stroke is given from a lateral perspective: vector M shows the movement direction, while vector D represents the total hydrodynamic drag, generically orientated and applied to the hypothetical barycentre of the swimmer.

2.4.1 Passive and Active Drag

Many researchers have divided hydrodynamic resistance into passive and active drag [13][14]. Passive drag is defined as the resistance created by a swimmer when he does not move; it has also been defined as the resistance generated by the non-propulsive parts of the athlete's body, i.e. the whole body not including hands and forearms [14]. Active drag is defined as the resistance generated by the swimmer's movements; it can be seen as a composite quantity that includes both the passive drag and the propulsive, 'residual' thrust generated at a given velocity and stroke rate [2][14]. Passive drag can, furthermore, be split into frictional, pressure-viscous and wave drag, for more accurate measurements. The main limit of this "passive-active" approach, however, lies in the lack of direct applications of these concepts to the swimming techniques.

2.4.2 Frictional, Form and Wave Drag

Therefore, for coaching purposes, hydrodynamic drag has also been divided into frictional, form and wave drag, as suggested for the first time by Karpovich (1933) [15] and later defined by Sheehan and Laughrin (1992) [16].

i. Frictional Drag

Frictional drag is developed when water passes over a rough surface, swirling in a tangle of microscopic eddies which generate a turbulent flow and produce a loss of power, efficiency and speed. Anyhow, frictional drag is accepted to be the smallest component of total drag, especially at high speed, as it has a linear relationship to the swimmer's velocity (Figure 3).

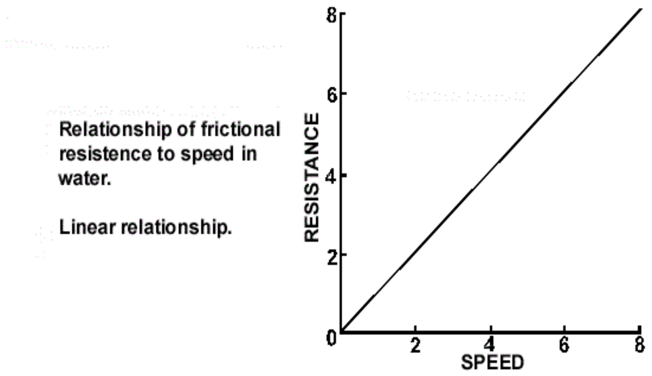

Figure 3. Frictional drag [10]

ii. Form Drag

Form drag is caused by a pressure differential between the front and the rear of the swimmer. It depends on the fluid density, on the swimmer's velocity and on his/her shape (geometry), especially on the body's cross-sectional area, which generates a frontal resistance. It has a quadratic relationship to the swimmer's velocity (Figure 4). Form drag is not always an adverse effect: it is, indeed, critical to propulsion when considered on the hands and forearms, as we will later see.

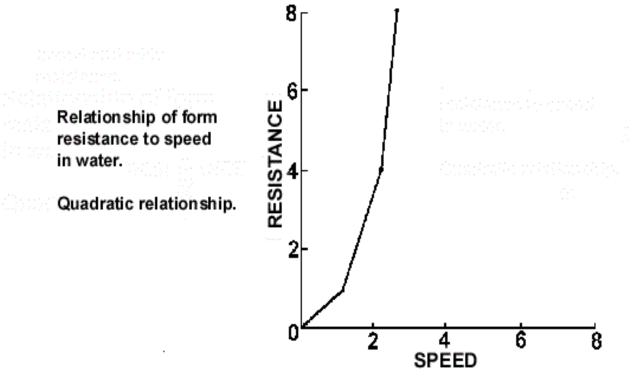

Figure 4. Form drag [10]

iii. Wave Drag

Wave drag is the third component of hydrodynamic drag. It arises when a swimmer creates surface waves, wakes and turbulence. As explained by the Principle of Conservation of Energy, surface waves take the energy they carry from an outside agent, namely the athlete, who consequently loses power. Since it scales as the cube of the swimmer's velocity (Figure 5), wave drag represents the most deleterious component of hydrodynamic resistance.

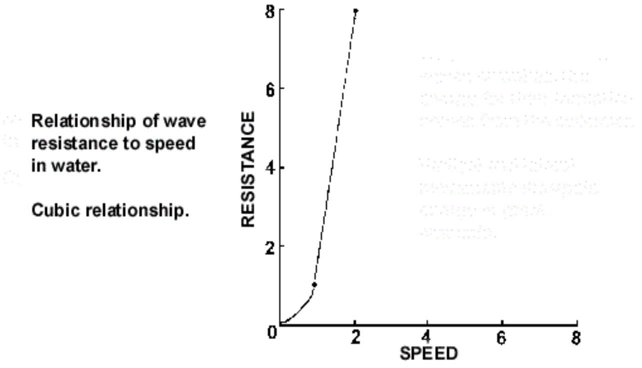

Figure 5. Wave drag [10]

2.5 Thrust and Hydrodynamic Lift

Hands and forearms are the parts of the swimmer's body which mainly generate thrust, even though, in certain cases, also legs and feet slightly contribute to propelling the athlete. Many researchers, starting from Counsilman [1], have advanced the idea of propulsion as "drag backwards", i.e. a drag force - more precisely, form drag - acting in the same direction of the athlete's movement direction, suggesting that hands and forearms should be considered as bluff bodies[2] [9]. Several studies, on the other hand, have pointed out the importance of the lift forces generated by the hand, which can, therefore, also be considered as a quasi-airfoil [4][17]: indeed, some scientists in the past promoted Bernoulli's Principle as the main justification for considering the contribution of lift forces to thrust during the pull. Anyhow, it has been proven that this Principle is an inappropriate model to explain propulsion in swimming, since it cannot predict or explain drag forces [10]. The hydrodynamic lift (L) can be expressed as

$$L = c_L \frac{1}{2} \rho V^2 S$$

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[2] *A 'bluff body' is defined, in aerodynamics, as a body that, due to its shape, has separated flow over a substantial part of its surface. Pressure drag is the predominant type of resistance generated by bluff bodies.*

where ρ represents the fluid density, S is the projection surface of the swimmer, V is the swimmer's velocity and c_L represents the lift coefficient. Disputes on which of the two forces - lift or drag - is predominant in the creation of the swimmer's propulsion have been carried on: however, nowadays the scientific community agrees that, when considering thrust in the context of competitive swimming, both of them should be taken into account, and their combination will give the resultant propulsive force [10].

In Figure 2, an example of lift and drag forces acting on the hand (and/or forearm) in all competitive swimming strokes is given from a lateral perspective. The line of flow is the direction in which the hand moves. The drag force acts opposite and the lift force acts at 90 degrees to the line of flow, the resultant force is derived from the drag and lift components. The angle of attack of the hand in this example is its angle to horizontal. We observe that no indication is given to the line of propulsion because forearm actions may be contributing to propulsion as well as reacting to another body movement: it is incorrect to infer that the line of flow should always coincide with the line of propulsion [10].

3. Whole-body, observation-based studies

This chapter is dedicated to several studies conducted by the researchers on the physical quantities previously defined. We will discuss some experimental results, based on the observation of a large variety of athletes during laboratory tests and competitions, which aim to suggest the most effective ways of perfecting their swimming technique and, therefore, improving their performance.

3.1 Studies on Hydrodynamic Drag

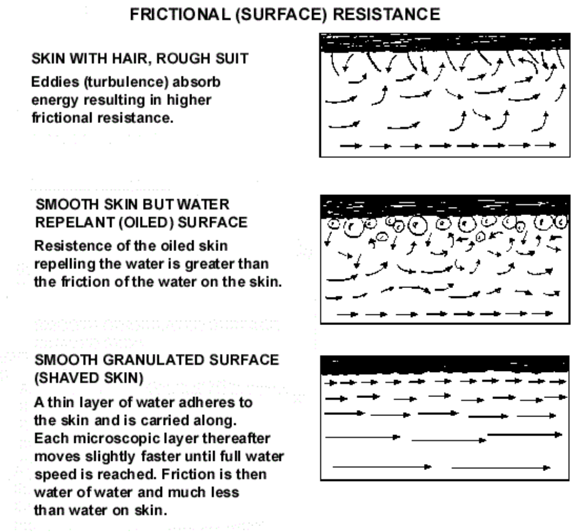
In Chapter 2, hydrodynamic drag has been introduced, and it has been pointed out that minimising its effects on the athlete's body is fundamental to achieving higher velocities.
As explained in Section 2.3.1, some studies have divided hydrodynamic resistance into passive and active components. This division represents a simple way to evaluate drag during a swimming event, although researchers have focused their attention mainly on the passive component, since measuring active drag without disturbing the natural swimming movements can be difficult [13]. Anyhow, several groups of scientists tried to develop different techniques to determine the active component in the 70's [18][19][20], while the so-called M.A.D. (Measure Active Drag) system was created in the mid-80's [21]. A more recent study, conducted by Takagi et al. (1999), has succeeded in determining active drag more precisely than before, by the development of a new device and methodology, and obtaining an experimental equation that can predict the active drag within a range of Reynolds number equalled the swimming velocity [2]. Toussaint (2002) has pointed out that also velocity oscillations have to be studied deeply, and that the position of the head and the body in the different strokes has a great influence on passive and active drag determination [3], hence the need to gather drag data on competitive swimmers in relevant positions. Nevertheless, since this method's results are not directly applicable to the swimming techniques, dividing hydrodynamic resistance into frictional, form and wave drag seems to be a preferable approach (Section 2.3.2).

3.1.1 Frictional, Form and Wave Drag

Let us therefore focus on the studies which follow Karpovich's division.

i. Frictional Drag

Skin, hair, swimsuits are all examples of what can cause friction whilst a swimmer moves through the water. In order to find a way to reduce it, some scientists have studied the impact of different types of swimsuits, their materials and their microstructure on the performance [7][22], while others have pointed out the importance of shaving hair off the body and legs, except the forearms [23]. It must be emphasised that, anyhow, the frictional surface should not be perfectly smooth: having imperfections on the swimmer's skin or suit, which hold and carry water particles, causes a further reduction in drag, since friction only being between water and water is much less than between an extremely smooth skin and water (Figure 6) [10][24].



FRICTIONAL (SURFACE) RESISTANCE

SKIN WITH HAIR, ROUGH SUIT
Eddies (turbulence) absorb energy resulting in higher frictional resistance.

SMOOTH SKIN BUT WATER REPELANT (OILED) SURFACE
Resistence of the oiled skin repelling the water is greater than the friction of the water on the skin.

SMOOTH GRANULATED SURFACE (SHAVED SKIN)
A thin layer of water adheres to the skin and is carried along. Each microscopic layer thereafter moves slightly faster until full water speed is reached. Friction is then water of water and much less than water on skin.

Figure 6. Features concerning frictional drag in swimmers [10]

ii. Form Drag

Form drag is generated by a pressure differential between the front and the rear of the swimmer's body (Section 2.3.2). From an aerodynamics perspective, to minimise its effects, the athlete should swim as much streamlined as possible, i.e. at zero angle of attack, assuming the most hydrodynamic postures and creating the straightest and thinnest form while moving through the water. Shoulders and chest should create a gap in the water, and the hips and the legs should follow through that space [9][10]. Four examples of decreasing and increasing streamlining are shown in Figure 7 [10]:

A - a head-up position (hyperextension of the neck) in crawl stroke tends to curve the spine and sink the hips lower than necessary. Straightening the neck, i.e. looking to the bottom, produces a more favourable streamlining;

B - crossing the entry behind the head in backstroke causes a hip movement from side to side, increasing form drag: if the entry is made in a position where streamlining is not disrupted, form drag should be minimised;

C - the head-up position of the breaststroker causes the hips to sink, increasing form drag: this problem is accentuated if the arm action occurs under the body. When the head looks down, form drag is minimised;

D - excessive head lifting and neck hyperextension during breathing can cause the legs and hips to drop lower in the water, increasing form drag. When the head lift and neck movement are reduced, disruptions to streamlining and form drag are minimised.

As a result, in coaching terms, athletes should swim "as flat as possible": if an action or posture generates an increase in the cross-sectional area, then the progress through the water will be slowed.

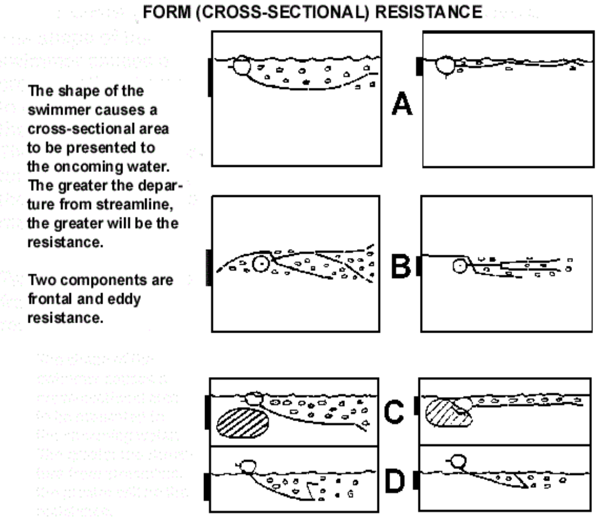


Figure 7. Features concerning form drag in swimmers [10]

iii. Wave drag

Over the past decades, wave drag has been studied in the context of competitive swimming despite the limitations in the available technologies and the complexity of the fluid flow generated by an "active" human body. Sheehan and Laughrin (1992) suggested that, due to its negligible effect when the swimmer is deep underwater, wave drag could be studied as a function of depth [16]. Vennell et al. (2006), indeed, found that total drag rapidly increases when the athlete approaches the surface, up to 2.4 times the drag measured with the body fully immersed and at the same swimming speed, and that wave resistance can account for about 50% of the total resistive force [25]. Researchers in the past suggested that swimming underwater was the best solution to avoid wave drag [26]: athletes actually took advantage by swimming completely submerged as long as they could during each leg of the race. Anyhow, we remind that nowadays FINA regulations state that the swimmer's head must break the water surface after the first 15 metres of each leg, and that therefore prolonged underwater swimming is not permitted. Other studies have drawn an analogy between the athlete and a vessel, both travelling on the water's surface [26][27]: Van Manen et al. (1988), and later Toussaint et al. (2000) and Vennell et al. (2006), identified Froude number[3] as an indicative parameter of wave drag's magnitude [25][27][28], although it is likely that the stroking arms passing through the water surface, ahead of the athlete's body, somehow alter it by modifying the characteristic length (Figure 8) [29]. Toussaint et al. (2000) also noted that another critical parameter is the so-called hull speed (V_h), defined, by analogy with a boat, as the speed at which the wave length equals the waterline length of the swimmer. Therefore, it depends on the square root of the swimmer's height [26][28]:

$$V_h = 1.248 \times \sqrt{H}$$

where H is measured in meters and V_h in meters per second. When V_h is achieved and exceeded, wave drag decreases while speed increases substantially: the swimmer is, in a sense, surfing his/her own bow wave, the performance benefiting greatly from this condition [9]. Other factors, such as the angle of attack of the body and the difference between supine and prone orientations, have also been researched [30][31][32]. With regard to the angle of attack, it has been observed that, whilst travelling near to the surface, bodies in an orientation where they have a negative angle of attack, i.e. hands lower than feet, show a less significant drag force in comparison to those orientated with a positive angle of attack. This result can be explained with the flow more efficiently minimising the interaction with the water surface by adhering to the dorsal part of the body when it is orientated with a negative angle of attack. Also comparing supine and prone orientations can be interesting, as swimmers often have to adopt only one position or the other – e.g. in front crawl the athletes must swim in a prone position, while in backstroke they must swim supinely. Results show that the supine orientation causes an earlier formation of the wave drag: the flow field is more disturbed while covering the ventral part of the body than the dorsal one, interacting earlier with the free surface and, thereby, creating waves earlier and more considerably. Therefore, since wave drag depends on the depth, the athletes swimming in a supine position should travel deeper into the water in order to minimise this type of resistive force and improve their performance. Moreover, any action that is not in a longitudinal horizontal direction, such as accentuated lateral or vertical

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[3] $Fr = \frac{V}{\sqrt{gL}}$, *where* V *is the body's speed,* g=9.81ms^{-2} *and* L *is the characteristic length.*

movements, creates undesirable waves. Four examples of common movements that increase wave drag are illustrated in Figure 9 [10]:

A - excessive diving at the butterfly entry;

B - excessive reaching across behind the head at the backstroke entry, which causes the hips to move laterally;

C1 - raising the head excessively to breathe, in crawl stroke, thus producing an exaggerated kick;

C2 - lowering the excessively raised head back into the water, thus moving a large volume of water.

It is important to note that these actions are doubly troublesome, as they also contribute to increasing form drag. A perfect technique is then fundamental to avoiding form and wave drag: any jerkiness in the swimmer’s style will cause an important increase in resistance.

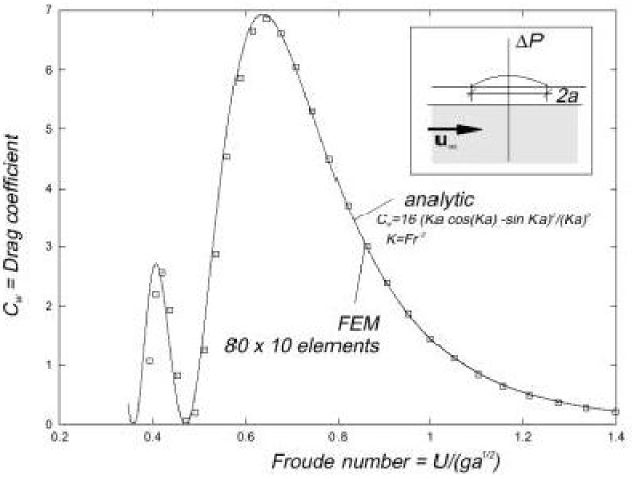

Figure 8. Wave drag coefficient with regard to Froude number [29]

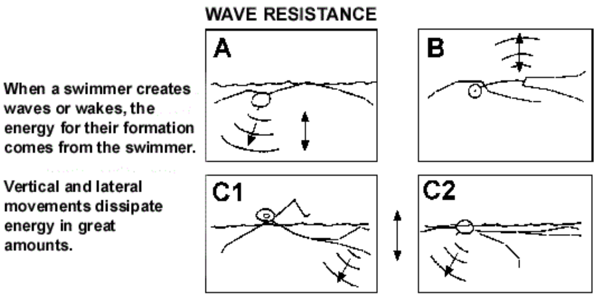

Figure 9. Features concerning wave drag in swimmers [10]

3.1.2 Differences between male and female athletes

We would like to observe that several of the results previously presented are not considering the differences between male and female swimmers: the different shape of the bodies is indeed of great significance to the flow field generated during swimming. Some scientists have researched into this topic [32][33], although it is necessary to further verify the theoretical findings experimentally, using accurate and reliable methods.

3.2 Studies on Thrust

Swimmers propel themselves mainly with their hands and forearms, which follow a particular path in each stroke, generating drag and lift forces, but also reacting to rotational effects of the athlete’s body. The complexity of these movements necessitates therefore a deep analysis of different physical quantities: researchers have often dilated on them separately, and tried to find out which one is the main contributor to propulsion. Rushall et al. (1994) assessed drag as the force with the greatest potential to increase thrust, emphasising, anyhow, that each component’s contribution depends on the phase of the arm motion, hence the need of studying every stage individually [10]. In their study, they stated that the angle of the hand-forearm to the line of flow or propulsion and their rotational movements are among the main factors that determine the contribution of lift and drag to thrust: during the pull, hands and forearms should move at right angle to the direction of propulsion in order to maximise drag, while in the entry transition the creation of lift forces should be prioritised. Moreover, the rotation of the hand should counterbalance lateral requirements: anyhow, these conditions are almost never fully satisfied, as all strokes require compromise positions and cannot be solely dedicated to propulsion. Contrary to many previous studies and basing on the results obtained by Cappaert (1992), Rushall et al. also identified forearms as the parts that contribute the most to the creation of lift and drag at high speeds [34], thus supporting the validity of the ‘elbows up’ position. Breaststroke represents the only exception in their analysis: due to the prevalence of lateral movements of the arms, in this style drag contributes little to forward progression, and low thrust is generated by the combination of drag and lift. Berger et al. (1995) measured the hydrodynamic forces acting on two models of a human hand and forearm, focusing their attention on the influence of several parameters (orientation of the model with respect to the flow line; velocity; size of the model; relative contribution of hand and forearm to the drag and lift coefficients) on total thrust and stating that propulsion can be more efficiently derived from lift than from drag [35].

Following this point, their research demonstrated that the magnitude of lift and drag depends on the orientation of the hand and forearm, and that hand is the main contributor to generating lift. Toussaint (2002) discussed the unsteady effects caused by the rotational movements of the arm, by analogy with a moth [3]. Using Bernoulli's Principle, he demonstrated that the pressure differential generated by rotations allows the water to be transported along the trailing side of the arm, from the elbow towards the hand, thus aiding propulsion: this "pumping" effect should be combined with the paddling actions of the hand-forearm and the movements of the legs in order to obtain the total propulsive force.

Throughout this section, a debate among researchers about which physical quantity makes the greatest contribution to thrust has been highlighted. It must be emphasised that these studies do not rely on the use of computational methods such as CFD, and that their conclusions are therefore based on theoretical concepts and experimental observations. CFD has been, indeed, extremely helpful in knowing more about the role of hands and forearms in the context of competitive swimming, although the discussion about the hydrodynamic forces is still open. Practical evidence seems to suggest that drag more efficiently contributes to thrust: swimmers are taught to avoid excessive lateral movements or S-shaped pulling patterns, which would, otherwise, sensibly affect the performance - i.e. the athlete would be slower[4]. However, it is widely accepted that both lift and drag forces have to be considered while studying propulsion in swimming, and that there is a need for further research to deepen the understanding of the topic.

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[4] *See Appendix.*

4. Computational studies

The last two decades have seen the integration of computational techniques into the study of competitive swimming: this modern approach has provided useful information about the swimmers' performance by a thorough analysis of propulsive and resistive forces, and has also been used to solve several complex fluid dynamics problems, thus rapidly becoming a complementary tool to the pre-existing experimental methods.

4.1 Computational techniques

Let us briefly introduce the methodologies which are nowadays used in human swimming research [36][37][38][39].

4.1.1 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics analyses and solves specific problems with computer-based, numerical simulations: for example, it can predict a fluid flow by replacing the Navier-Stokes equations with algebraic expressions that can be solved by iterative algorithms. Traditional CFD methodology is based on the finite volume approach: the spatial domain is discretized into small cells, on which velocity and pressure are defined, to form a three-dimensional volume mesh (or grid), and the equations are integrated over each control volume. Besides this methodology, which ensures a good degree of accuracy, there are emerging particle and hybrid-based approaches, such as the Smooth Particle Hydrodynamics (SPH) method, which provide better 3D visualisation and computational efficiency. The grid-based method typically uses stationary meshes, except for the geometry of the moving objects, in our case the swimmer, who is two-way coupled to the surrounding medium, as there is a mutual influence between the body and the water in the motion: the problem of studying the flow around a dynamic swimmer is indeed complex, and requires an extremely accurate approach. For this reason, when modelling the athlete, several assumptions are made in order to simplify the problem and reduce the computational costs: the swimmer is often seen as an articulated but rigid body to avoid issues related to skin's deformation, and the biomechanical modelling of muscles and bones is generally excluded from the study. Furthermore, the water surface, splashes and bubbles must be considered in the analysis of surface swimming, hence the need for a multi-phase flow modelling which can predict their shape. However, one of the major benefits of CFD lies in its ability to answer many "what if" type questions: it is possible to examine different situations, by modifying the critical parameters, without doing any experimental tests. Ergo, this tool offers the opportunity for non-invasive, controllable and repeatable experimentations, and provides researchers with meaningful results. CFD also represents a reliable device, whose commercial codes[5] are therefore applied to a wide range of swimming tests.

4.1.2 Swimming Human Simulation Model (SWUM)

SWUM is another computational technique, developed by Nakashima, Satou and Miura (2007) [40]. This approach requires much less computation time than CFD, since it does not solve the flow field, and can therefore be used to predict unknown and unmeasured situations. The peculiarity of this model is its representation of the swimmer's body, seen as a series of truncated elliptic cones on which the forces are calculated. SWUM analysis also considers the added mass and the unsteady fluid forces, including buoyancy and gravity, but does not take account of several factors, such as the effects of the surrounding walls on the performance or the mutual interaction of the limbs: a comparison with CFD results is therefore always needed.

4.2 The role of the hand and forearm

Researchers have recently tried to elaborate on the role of the hand and forearm from a computational perspective, in order to understand more about the generation of thrust in swimming and expand upon the previous experimental studies (Section 3.2). Bixler and Schloder (1996) were the first to use CFD while studying the flow field around a circular disk, which represented a simplified model of a swimmer's hand [41]. Despite several limitations, their work compared a steady flow and an accelerated flow, both normal to the surface of the disk, and showed that the unsteady effects caused by the acceleration of the hand during the pull phase contribute to a substantial increase in propulsive drag in comparison to the quasi-steady case. Moreover, they demonstrated that "unsteady" propulsive drag is directly proportional to the Added Mass Coefficient (k), which indicates how much water is grabbed by the swimmer's hand. Total propulsive drag (D_P) can therefore be expressed as

$$D_P = c_D \frac{1}{2} \rho V^2 S + k \rho \Omega a$$

where the first term is the drag force due to the steady flow (Section 2.3), whilst the unsteady effects are represented by the second term, in which k (the Added Mass Coefficient) is defined as the added mass divided by the mass of fluid displaced by the object, Ω is the characteristic volume of the body on which k is based and *a* is the instantaneous acceleration at time *t*. These results proved Counsilman's intuitive

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[5] *Such as Fluent® and STREAM®*

suggestion that swimmers should accelerate their hands - and forearms - during the pull, and that they should “catch” as much water as possible at the start of each stroke. Takagi et al. (2014) provided a more elaborate explanation for the effects of the hand’s acceleration: they found that irregular oscillations in the hydrodynamic forces - and therefore pressure differentials between the palm and the dorsum - are caused by a Karman vortex street, i.e. by the creation of clockwise and counterclockwise vortices alternately shed from the side of the little finger or the thumb [42]. Furthermore, they observed that, when the hand rotates during the pull, the direction of the bound vortex changes, producing a lift force: this discovery confirmed Toussaint’s theory about the ‘pumping effect’ (Section 3.2). Riewald and Bixler (2001) focused on the role of the arm, revealing that acceleration has a greater effect on arm drag than on hand drag [43]. They also found that drag forces are more influenced by unsteady effects than lift forces are, and that maximum hand propulsion is obtained when the palm faces directly towards the feet. Moreover, they stated that, due to a significant boundary layer separation of the flow from the hands and forearms, Bernoulli’s Principle should not be used to mathematically explain lift generation [4]. On the other hand, von Loebbecke and Mittal (2012) assessed lift as the main contributor to thrust in front crawl and backstroke, observing that, however, exaggerated sculling motions reduce the effectiveness of the stroke [44]. Cohen et al. (2015) adopted the SPH approach to study the role of the hand in freestyle swimming, suggesting that propulsion is the result of a combination of lift and drag. Their research also considered the effects of the free surface waves, and dilated on the creation of vortical structures during the pull, which can be exploited to enhance thrust if properly “recaptured” by legs and feet in their kicking motion [5].

As highlighted in this section, computational methodologies have considerably helped scientists to learn more about thrust generation. In spite of the different and sometimes opposite results, recent studies have provided more detailed information on how to improve the existing swimming and coaching techniques, which remains the principal aim of this field of research. CFD has also been exploited to analyse a particular swimming technique, the so-called ‘dolphin kick’, which represents the subject matter of this chapter’s next section.

4.3 The Dolphin Kick Technique

As the name suggests, the dolphin kick technique is inspired by the subcarangiform type of motion adopted by dolphins and similar cetaceans [45]: it consists of an undulating movement of the swimmer’s body (Figure 10), which exploits its three rotational joints - hips, knees and ankles - to create a propulsive displacement wave that grows in magnitude as it propagates down towards the toes. In this technique, the arms are outstretched and the hands held together in a streamlined position ahead of the head, while the orientation of the body depends on the swimming style and on the athlete's preference.

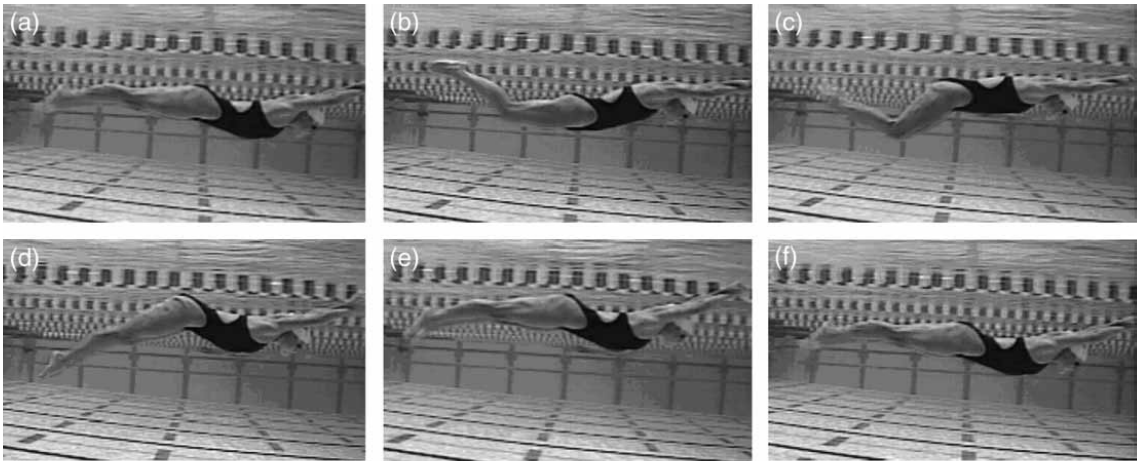

Figure 10. Sequence of six frames representing the typical movements in the dolphin kick technique [6]

The simplicity of the motion and the absence of effects such as surface waves and splashes, due to the significant depth at which this technique is performed, make dolphin kick a relatively easy stroke to model and study for fluid dynamicists, especially from a computational point of view. Lyttle and Keys (2006) proposed a quasi-steady simulation of the technique [46]: anyhow, since propulsion in swimming is also generated by unsteady mechanisms, their analysis was rather limited. A fully unsteady CFD approach was used by von Loebbecke et al. (2009a) to elaborately examine thrust generation and wake dynamics for two different models (one male and one female) [6]. They observed that propulsion in this context is strictly connected to vorticity, and that vortex structures are mainly shed by the regions below the knees, while in the other parts of the body the flow is nearly fully attached. The simulations showed that a significant three-dimensional vortex ring is produced at the end of the extensive phase of the kick (Figures 11 and 12), inducing a highly directed jet for a relatively long time and, thus, creating the maximum overall thrust.

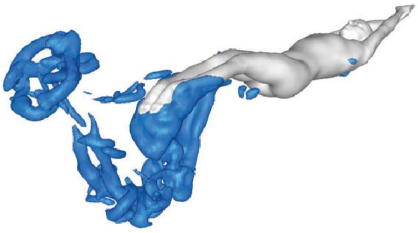

Figure 11. Vortex structure generated during a human dolphin kick. The three-dimensional vortex ring is clearly visible on the left side of the image [47]

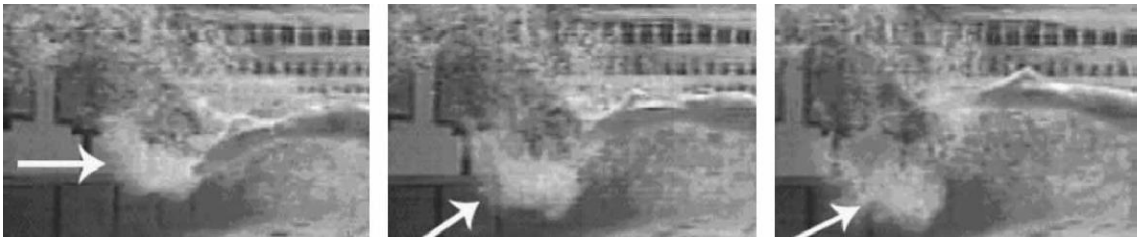

Figure 12. Images from the video footage of the dolphin kick. The white arrows help indicate the vortex ring structure shed by the feet [6]

Their analysis also explained the asymmetry in the forces produced during the two portions of the kick as a consequence of the asymmetry of the knee and ankle joints, and indicated feet as responsible for most of the thrust production, pointing out that a focus on foot motion and ankle flexibility is required to improve this swimming technique. Another study by von Loebbecke et al. (2009b) discussed the propulsive efficiency of the dolphin kick, defined as the ratio of useful, thrust-producing work to the total work done by the swimmer in one stroke, concluding that its high mean value (about 21%, according to their work) is mainly due to the absence of wave drag [47]. Moreover, contrary to previous researches, they found no direct correlation between efficiency and the Strouhal number[6]. Cohen et al. (2012) studied the forces generated during the dolphin kick motion on a “tethered” and on a “dynamic” swimmer using the SPH method [48]. Dilating on the works by von Loebbecke et al. (2009a), they found that, at high speeds, the contribution of the up-kick to propulsion also becomes important. Furthermore, they discovered that heightening the stroke frequency causes both a substantial increase in force and a linear increase in velocity: this result suggests that, by increasing the underwater stroke rate, athletes should be able to improve their performance without losing efficiency.

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[6] $St = f\frac{A}{V}$ *, where f is the kick frequency,* A *is the total toe amplitude of the kick and* V *is the swimmer’s average speed.*

5. Conclusions

Throughout this study, it has been emphasised that the principal aim of the research into the fluid dynamics of competitive swimming is to allow the athletes to perfect their technique and, therefore, enhance their performance. Since Counsilman's first publication in 1968, scientific methods have evolved from observation-based studies to the use of up-to-date numerical and computational tools that have offered new insights and provided information and results which were unobtainable before. CFD represents the most promising and powerful instrument in the hands of the twenty-first century swimming sports scientist, as it has the potential to bring this field of research to a greater level of understanding of the physical phenomena involved in the study. There is, in particular, a need for data acquisition and further research on wave drag: improved numerical models should be able to provide more detailed information on the generation of surface waves, splashes and bubbles. Furthermore, a higher degree of accuracy of the unsteady CFD approach must be ensured, in order to know more about the contribution of non-steady effects to swimming propulsion. Complementary methodologies for flow visualisation are also essential to verifying results from numerical simulations, while other software packages, such as SWUM, can offer practical benefits, making scientific knowledge available and meaningful for coaches and athletes. Finally, energetics, seen as the linking between fluid dynamics and biomechanics, represents the next challenge in the science of competitive swimming: evaluating the swimming techniques in terms of speed, hydrodynamic net thrust and power - which can be considered as an equivalent expression for swimming efficiency - with increasing precision will allow scientists to provide coaches with more useful and constructive suggestions and, eventually, identify the most effective way of swimming.

Appendix: The S-Stroke

The S-stroke is a particular swimming technique which consists in a curvilinear, S-shaped movement of the hand and arm during the pull. This stroke was first introduced by Counsilman (1968), who thought that the combination of the bluff body thrust and the lift generated by the transverse motion of the hand would result in a greater total propulsive force in comparison to that of the traditional "straight" pull [1]. Anyhow, many researches have shown that exaggerated lateral movements or sculling motions are actually detrimental to the performance (see Chapters 3 and 4), and Wei et al. (2014) succeeded in demonstrating the ineffectiveness of the S-stroke mathematically [9]. It must be underlined, therefore, that scientific results always have to be deeply analysed and discussed before drawing any practical conclusions: as shown throughout our study, lift and drag are, indeed, important components of the total propulsion, but any technique or motion in which one of these two forces is neglected will produce an overall reduction in thrust magnitude.

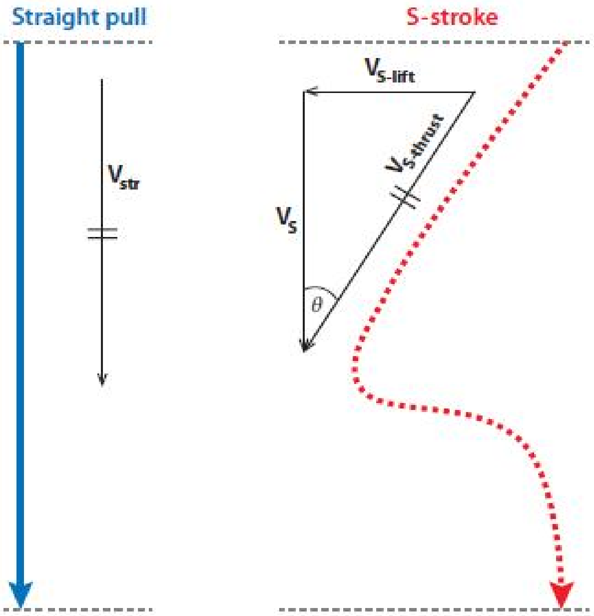

Figure 13. A comparison between the trajectories of the hand in the straight pull and the S-stroke (note that the stroke length and the hand-arm velocity are the same for both cases) [9]

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