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VORTICES AND PROPULSION

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A review of the general theory of swimming propulsion is presented relating this with knowledge about vortices in steady and unsteady flow conditions. Three methods of flow visualisation have been used in the experiments: a) injecting air bubbles close to big toe during undulatory underwater swimming and breaststroke kick; b) putting reflective particles in water to see hand short movements and; c) injection of air bubbles in the swimming pool creating a “bubble wall”, making it possible for the swimmer to cross and to swim along it. The results of the experiments showed that: a) vortices are generated during different phases of the stroke and during the downward kick in undulatory swimming, flutter kick and breaststroke kick; b) when the hand suddenly changes the direction of its movement the starting vortex is detached from the hand and; c) the size and movement characteristics of the vortex seem related to propulsion obtained by the hand and foot movements.

KEY WORDS: swimming propulsion, vortex, flow visualisation, bubble wall.

INTRODUCTION: THE BASICS OF SWIMMING PROPULSION: The total mechanical power (Po) produced by the swimmer (assuming a constant velocity) equals the power to overcome active drag (Pd) plus power expended in giving masses of water pushed away a kinetic energy change (Pk) (Toussaint, 1992):

$$Po = Pd + Pk \quad (1)$$

(Counsilman, 1971) stated that efficient propulsion is obtained by pushing a large mass of water a short distance without much acceleration. Greater efficiency in water is achieved by moving a large amount of water a short distance than by moving small amounts of water a great distance. These statement were developed after observing how good swimmers pull in the water with complex 3D trajectories that show continuous changes of the direction of the hand’s pulling path. Later (Martin, 1989) speaking about the fundamental principles in swimming asserted that swimming by propelling water, one may achieve a given amount of thrust either by accelerating a large mass of water to a small velocity or vice versa. It turns out that the former choice is more efficient. The thrust is equal to the momentum, **mv** (the product of mass and velocity) of water that is propelled backwards each second. The energy required to accelerate this water is proportional to $\mathbf{mv^2}$ **(2)**. One sees that the thrust is independent of the relationship between **m** and **v**, but the energy required is less if **v** is small. Thus it is more efficient, mechanically speaking, for a swimmer to move a large tail (or flipper or hand) slowly than a small one rapidly. (Butovich & Chudovskiy, 1968) in a very interesting book written in Russian about front crawl biomechanics explained graphically the differences between planar and 3D curvilinear pulling paths. The second path illustrates better the previous statements (see fig. 1).
(Vogel, 1997) speaking about the propulsion of bivalve molluscs stated that the problem is that thrust is produced most efficiently by giving as large a mass of water as possible the smallest incremental speed, just the opposite to what a jet does. An expert in water animal propulsion obtained the same conclusion as our swimming experts.
It is necessary to make a brief remark now, about how this force is produced by the swimmer and the implications on the propulsion theory. The hand displacement is the result

of a muscle contraction. Muscles such as latissimus dorsi, pectoralis major, teres major and deltoides are mainly responsible for arm pulling (Hamill & Knutzen, 1995).

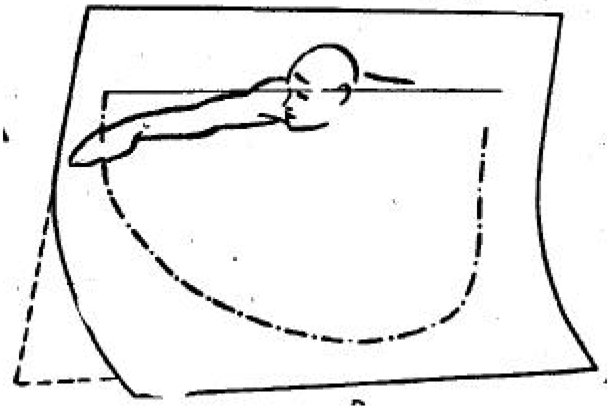


Figure 1: Graphical explanation of differences between a planar and a 3D curvilinear pulling path in freestyle (Butovich & Chudovskiy, 1968).

Therefore the swimming propulsion is the result of a muscular force applied by the hand, forearm and arm to the water (see fig.2). Shortening the muscle impels the body displacement forward while the hand "seems" to be in a fixed point. Conceptually we can set up differences between two forces: *muscular force and applied force*. Swimming training attempts to develop muscular force and muscular endurance but is this muscular development useful directly to improve swimming speed?
In our studies, we recorded propulsive force during tethered swimming at velocity equal to zero (Arellano, 1992). We found that after a cycle of training oriented to improve muscular force out of the water, the improvement of recorded force was near 15% ($p<0.01$) but the swimming velocity in short distances did not improve. This situation can be explained because, while the muscular force increased with weight training the applied force did not follow in the same way. It is necessary to train more specifically (in the water) to transfer this muscular force to applied force. Applied force involves a development of the feeling of water: an specific kinaesthetic and tactile sense. The development of modern training in swimming has to be oriented to improve applied force and this force can only be developed inter-acting directly with the water. This situation explains how many world-ranked swimmers do not do power training out of the water, yet they are very fast swimmers and they have in some cases less muscular force but much more applied force.

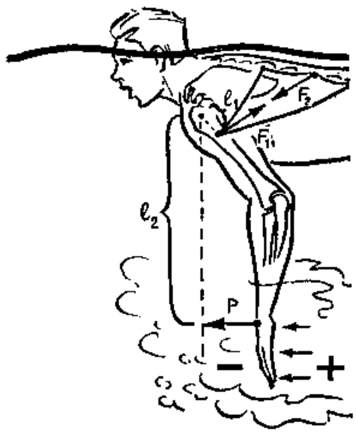


Figure 2: Graphical explanation of how the propulsion is generated by a muscular contraction in freestyle swimming (Makarenko, 1975)

The next problem is to explain how the swimmer generates applied force. For many moving objects, the surrounding fluid (air or water) can exert a sideways force that is subtler than the drag force. The forces that can make a spinning ball swerve or produce lift in an aeroplane are produced by a common cause: a net circulation of the fluid around the object. This flow can be separated into translating and circulating components. In the case of a ball the reason for this circulation is clear: the fluid in contact with the ball rotates with it (see figures 5a and 5b). The force perpendicular to the flow is directly proportional to the rotation rate, and can be explained in terms of Bernoulli's law, which relates flow rate and pressure. The fluid moves faster on one side of the object than the other, and the resulting pressure difference exerts a force that can lift the ball or cause it to swerve. Although an aeroplane wing or airfoil does not rotate, its shape and/or the angle of inclination in the flow produce the same effect on the fluid (see figures 6a and 6b). In this case the fluid circulation around the wing is not known. However, it can be determined by the Kutta-Zhukovski theorem, which states that the circulating component around the airfoil is matched so that the flow field continues smoothly past the back edge of the wing (Belmonte & Moses, 1999). The circulation concept and others such as lift and drag were cited for first time in a Biomechanics book by (Hochmuth, 1973) in 1966.

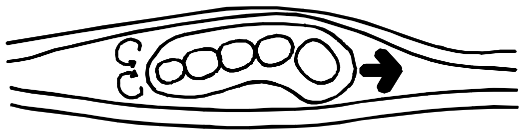


Figure 3: Flow behaviour during a linear hand's movement with an attack angle of 0º and a sweep-back angle of 0º. The drag and lift components of the propulsive force are small. Two stagnation points are located rear and forward where the flow velocity is equal to zero (Marchaj, 1988).

Figure 4: Flow behaviour during a linear hand's movement with an attack angle of 90º and a sweep-back angle of 0º. The drag component of the propulsive force is high and the lift component is small. Two big vortices are created on the back of the hand inside the wake. There is a considerable relationship between the boundary layer separation and the formation of the wake. The size of the wake and the pressure within it determine the magnitude of the pressure drag (Douglas et al., 1995) (a). These vortices are unstable and a vortex street is developed. This situation makes difficult to keep the pulling path straight, feeling lateral oscillations on the hands (b).

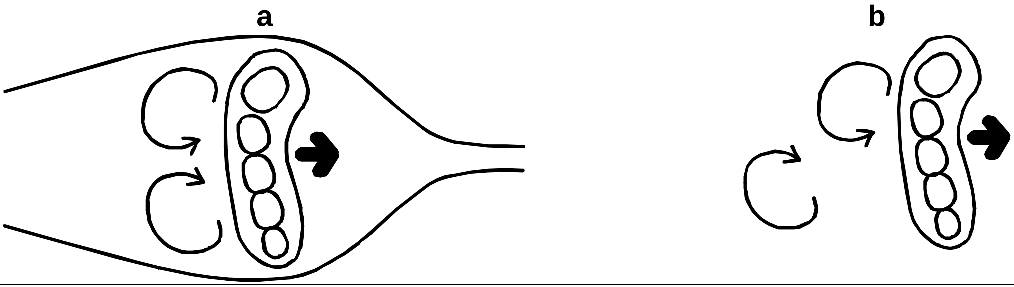
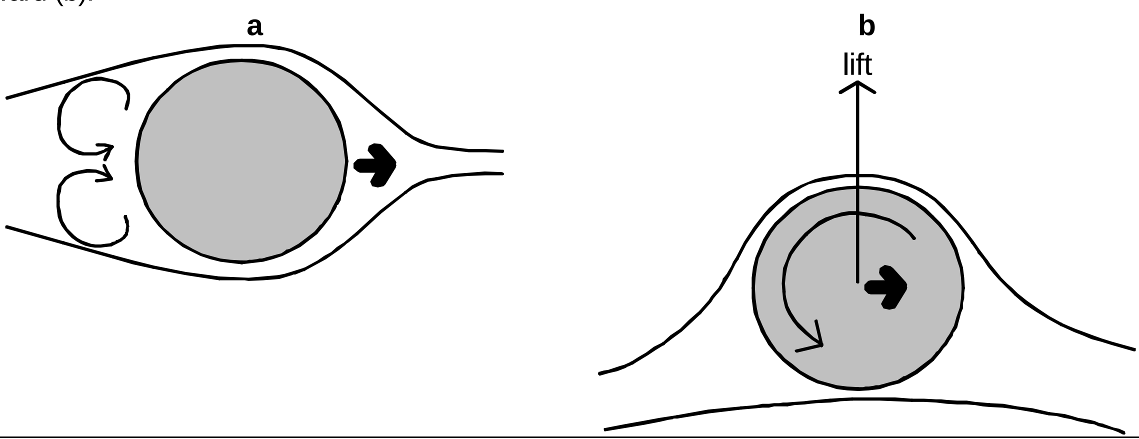


Figure 5: A ball without rotation only develops aerodynamic drag and some instability if a vortex street is created (a). The same ball with rotation mimics a airfoil by distorting the flow field in a way that creates aerodynamic lift. Because of the rotation the air flowing over the top of the ball is accelerated to the rear and the air flowing under the ball is retarded (Larrabie, 1980). The velocity differences results in an imbalance of forces (according Bernoulli's Theorem) that pushes the ball upward (b).



The figure 7a shows an hand section and some of the most important terms related to it: a) leading edge or edge facing the direction of flow; b) trailing edge or the rear, downstream, edge; c) chord line or a straight line joining the centres of curvature of leading and trailing edges; d) camber line or centreline of the hand section and; e) angle of attack or angle between the direction of the relative motion and the chord line (adapted from (Douglas, Gasiorek, & Swaffield, 1995). To define the real position of the hand in the water another term plays a roll the sweep-back angle. This angle defines the leading edge of the hand relative to the fluid flow and is found by projecting the hand velocity vector onto the plane of the hand (Payton & Bartlett, 1995). Similar variables can be applied to know the feet position (Sanders, 1997). The variations on the angle of attack produce a modification in water behaviour in the wake generated on the back of the hand (see fig.3, 4, 5 and 6). Two different forces are generated with different values related to the attack angle and their vector addition is the resultant force or net propulsive force. Schleihauf (1979) investigated lift and drag forces on hand models in an open-water channel at certain steady-state flow conditions. His experiments showed a specific relationship between drag and lift coefficients and the attack angle (see figure 9). The Schleihauf experiments were replicated by (Berger, Groot, & Hollander, 1995) and she stated in her conclusions: a) It has been shown from a theoretical point of view that propulsive forces during human swimming can be more efficiently derived from lift forces then from drag forces. At high lift forces the loss of energy will be minimal. Consequently, a proper technique should generate as much lift as possible; b) The data obtained indicate that the optimal orientation of the hand with respect to the direction of motion of the hand would be about 55º for a thumb-leading orientation and 25º for a little finger-leading orientation. The lift force will be as high as possible at these orientations of the hand; c) Swimming with a sculling motion in which the hand velocity is always higher than the velocity of forearm might be much more efficient than swimming with a 'push-pull' stroke, in which the hand and forearm velocity are much more similar. Using three pressure force transducers on the palm and three more on the back of the hand (Redondo & Cano, 1979; Redondo, Morris, & Cano, 1981) and calculating the lift force from the Kutta-Zhukovsky equation, he found that the lift and drag forces were both responsible for swimming propulsion during the propulsive movements in freestyle.

Figure 6: When the hand is moving with an angle of attack bigger than zero the fluid has a tendency to go around the trailing edge of the hand. The flow breaks away from the edge and so-called starting vortex begins to operate between the trailing and the rear stagnation point that is now situated on the upper surface (back of the hand) (a). As the starting vortex rotates, a counter-rotation develops round the foil in the opposite direction to that of the starting vortex because the rotation of the starting vortex (angular momentum) cannot be created in a physical system without reaction: circulation. (Marchaj, 1988). The circulation around the hand develops as the ball of in figure 6b, a lift force perpendicular to the direction of the hand's movement.

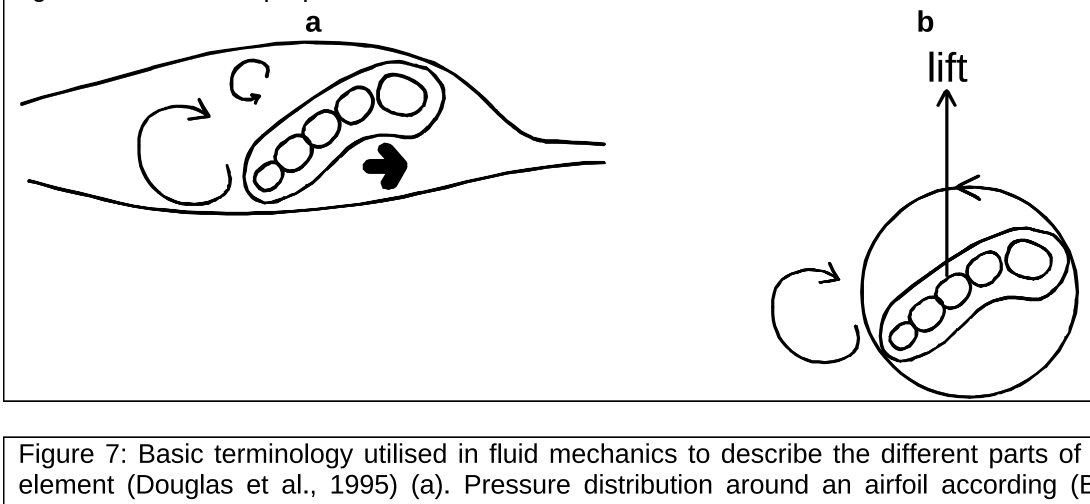
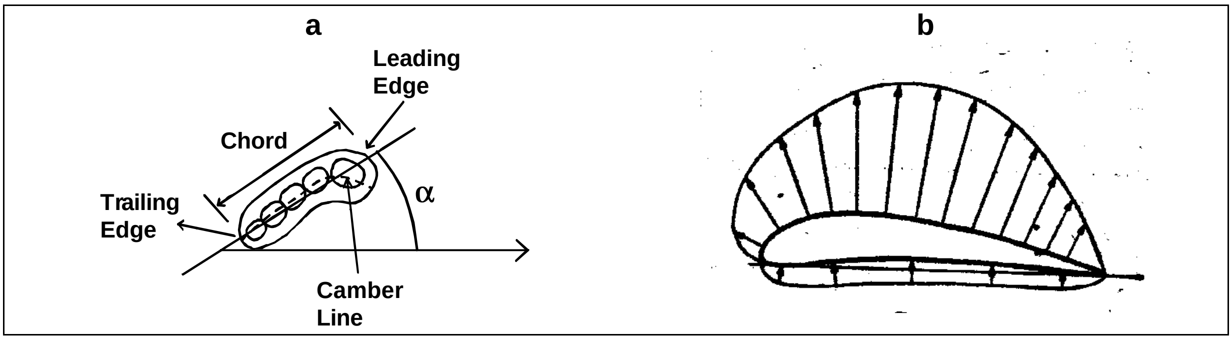


Figure 7: Basic terminology utilised in fluid mechanics to describe the different parts of propulsive element (Douglas et al., 1995) (a). Pressure distribution around an airfoil according (Butovich & Chudovskiy, 1968) (b).



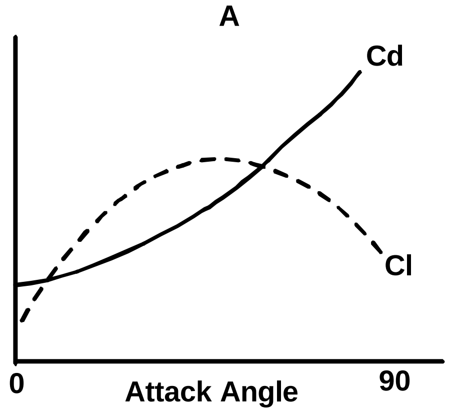


Figure 8: Drag and lift coefficients obtained changing the angle of attack of a flat plate from 0º to 90º (Hochmuth, 1973). The lift and drag coefficients increase from 0º to 50º in a similar value and from 50º to 90º as drag increases and lift decreases (a).

But, a big controversy was developed over the last decade about the importance of each force component. Sprigins and Koehler (1990) recommended using a Newton's model instead of Bernoulli's model to explain dynamic lift in sport. Rushall, Holt, Sprigings, and Cappaert (1994) stated "if lift forces were working fully in the Bernoullian mode, the flow of water across the back of the hand would be undisturbed, … When observation of turbulence and bubbles are made, lift forces will not be dominant in contributing to propulsion". These authors in their practical implications recommend "swimmers should be taught or encouraged to feel that they are pushing against the water in a predominantly backward direction". Another well-known author Ernie Maglischo showed in his opinions an evolution from lift to drag and he said: 1) "Once the principles of using lift to generate propulsion are understood, coaches and swimmers can apply them to improve the stroke mechanics of competitive swimmers" (Maglischo, 1982). 2) "The theory subscribed to in this text is that the most important propulsive principle they are applying is Newton's third law of action-reaction, not Bernoulli's theorem (Costill, Maglischo, & Richardson, 1992). 3) "…sculling is the central propulsive mechanism regardless of the theory you select. Whether swimming propulsion is drag-dominated or lift-dominated does not change the fact that the majority of world-class swimmers are using sculling movements to propel themselves forward" (Maglischo, 1995). 4) "… I think I've been wrong, and I've provided you with a lot of misinformation over the years….Now, a little later on I came along and because I was disenchanted with the Bernoulli theorem, I tried to come up with another idea for propulsion. And, I went back to Newton's third law of motion, that if you're pushing water backward you'll go forward…. I now believe that propulsion is drag dominated…" (Maglischo, 1999).

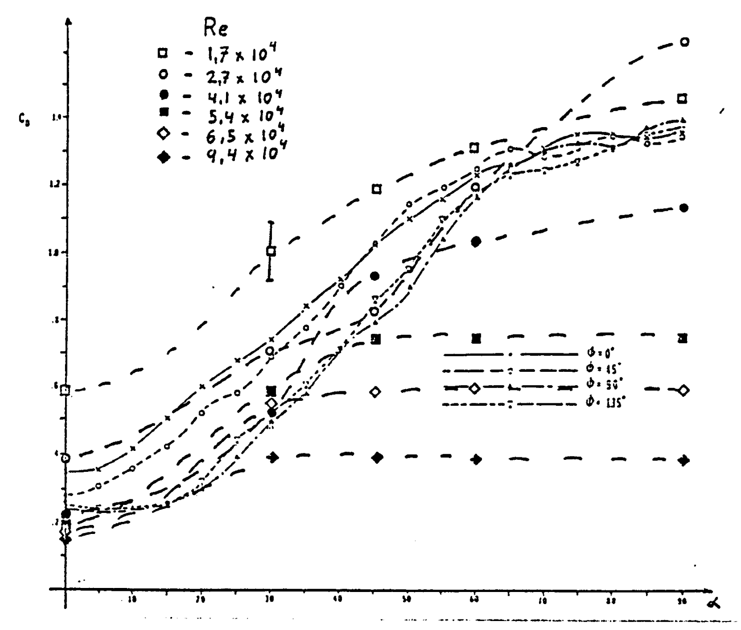


Figure 9: Hand drag coefficients obtained experimentally at different water speeds by (Redondo, 1987) related to the Reynolds number (Re) and compared with those obtained by (Schleihauf, 1979). The drag coefficient decreases when the Reynolds numbers increase. The values of the drag coefficient reach similar values from 20 º to 90º when Re is high (9.4 x 10^4).

Personally, I don’t think Mr Maglischo was so wrong before and nor is he so totally right now. Many of the “new theories” are based in the forces shown by using underwater video-recording where the average errors in lift- and drag-coefficients could become 27% and 20%, respectively (Payton & Bartlett, 1995). When you are increasing the speed of the hand, the drag coefficient is not increasing linearly because is affected by Reynolds’ number (criterion which determines whether flow is viscous or turbulent). The drag coefficient is considerably smaller during the turbulent boundary layer than for the laminar boundary layer because the wake is narrower (Douglas et al., 1995). In experiments developed by (Redondo, 1987) he measured the drag coefficients in a water channel of models of hands at different velocities of flow. When the drag coefficient (α = 90º) was related to the Reynolds number, at high values of Re the Cd decreased until values similar to attack angles were close to zero (see fig.9). Thus, knowing the water is mostly turbulent when the hand is moving in the water, is it exactly correct to tell swimmers they have to move the hand directly backwards?

Moreover, in some cases the propulsive theory is being explained in a very analytical way, for example saying there is four theories for explaining propulsion: drag theory, lift theory, vortex theory and sculling theory (Maglischo & Maglischo, 1995). But this is not true, there is only a theory of the propulsion that includes drag and lift components, flow circulation, starting vortex, bound vortex, Bernoulli’s principle, Magnus’ effect, Kutta-Zhukovsky’s theorem, steady and unsteady flows and so on. Or as Colwin (1999) said “instead of belabouring the lift versus drag argument, we need to move on and learn more about the way the water reacts when we swim”. New observations on unsteady effects have shown, for example, that hydrofoils with an impulsive start and high angle of attack can produce significant transient lift force. This finding suggests that the application of unsteady fluid dynamics to competitive swimming may rejuvenate the debate on the nature of thrust forces DeMont (1999). In the next pages we will try to give information about how the water reacts during the hand and foot movements in the water.

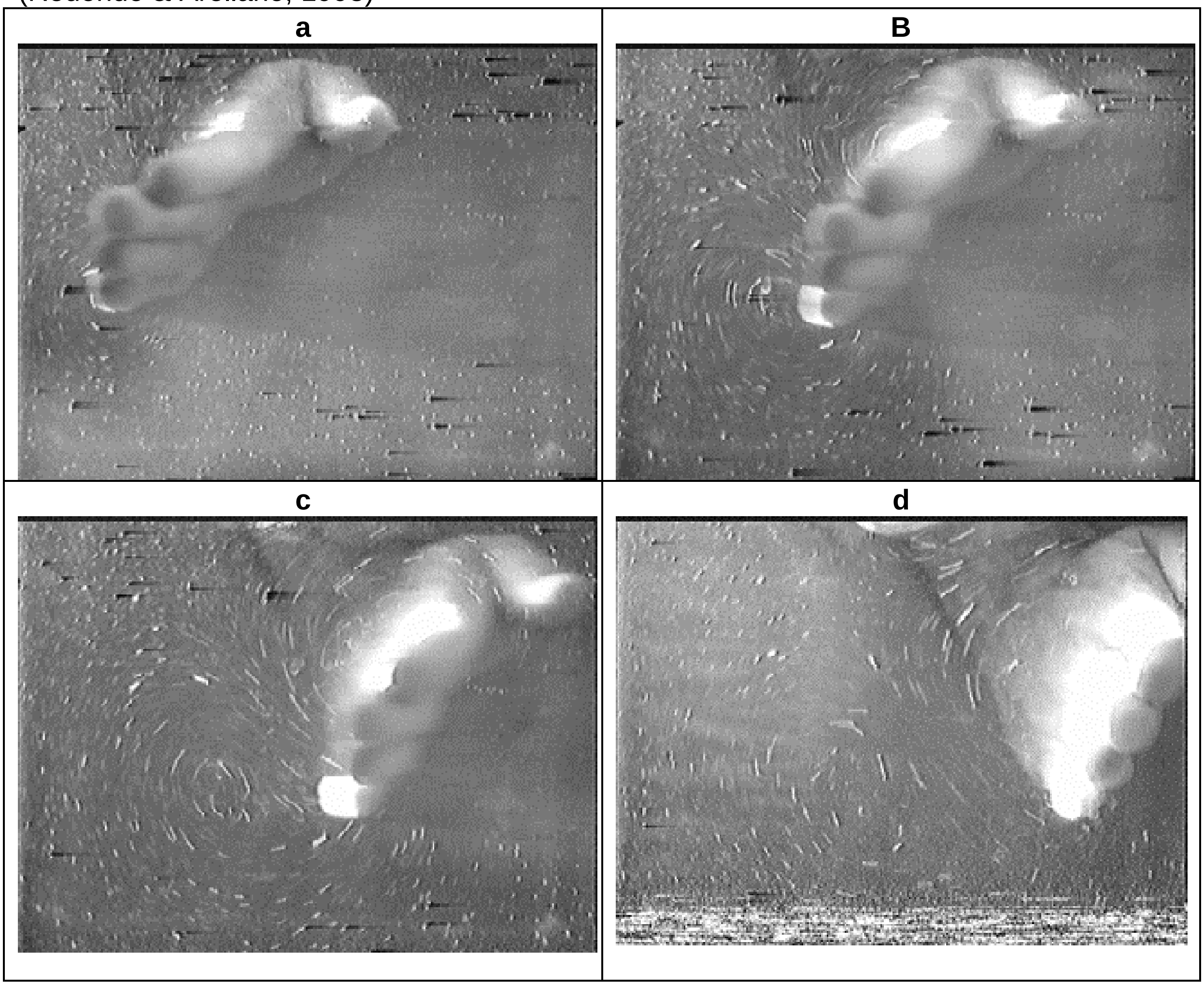
WHAT IS A VORTEX? In common usage, by vortex we usually mean a whirlpool, or a circular cavity formed by a liquid in rotation. Vortex in fluid mechanics means a region of fluid bounded by the so-called vortex lines, whose tangents at all points are parallel to the local directions of vorticity. The vortex lines, which are the axes of rotation, have to be either closed lines, or begin and end on the boundaries of the fluid or on the points in regions of

infinite vorticity. A vortex induces an external fluid motion. (Tokaty, 1994). A vortex is a form of kinetic energy, the energy of motion. A shed vortex represents the energy produced by the swimmer and "given" to the water. In fact, when you see the vortices produced by the swimmer in the water, you are actually looking at the swimmer's propulsion. Without the resistive friction provided by vortex turbulence within a fluid, no tractive force would be provided.(Colwin, 1999).
The theories applied to develop mathematical models of the vortex behaviour come from the Kutta-Zhukovsky Theorem: When a vortex (or equivalent rotating body) of circulation Γ moves in a uniform fluid of density ρ with the velocity ***v*¥**, it produces a force ρ ***v*¥**Γ, per unit length, perpendicular to the direction of ***v*¥** and to the axis of the vortex.

L = ρ ***v*¥**Γ

The Zhukovsky theory of conformal transformation shows that when a flow with circulation around a circle (vortex) is transformed into a flow past an airfoil, the circulation remains the same. A circle and a wing can replace the airfoil by a circular cylinder (long vortex). A bound vortex is imagined to be inside the wing, and confined to the wing. Because the aircraft wing can ever be infinitely long, the bound vortex too, must have an infinite length, or span. Zhukovsky suggested that his bound vortex twists at the tips of the wing and thus a horseshoe vortex system is formed (Tokaty, 1994).

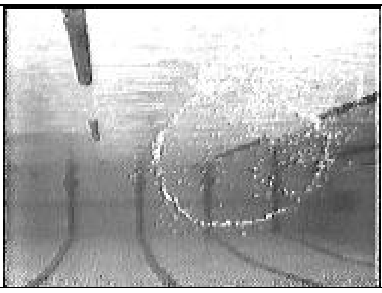
Figure 10 : Development of initial vortex in a rectilinear movement of the hand. Thanks to the flow visualisation you can see both vortices and how different in size they are. (Redondo & Arellano, 1998)



In steady-state situations, such a aeroplane cruising at constant speed and altitude, the Kutta-Zhukovski theorem has been shown to be correct. But what about an unsteady situation where the wings move vertically or flap (Belmonte & Moses, 1999). Many studies in the animal world show how vortices are generated during the flight of birds and the propulsion of fishes. In more simple situations such as a sheet of paper falling through the air or metallic plates through water we can observe how vortices are created at the end of their lateral movements while they are changing their falling direction. This situation is specially important during the changes of direction of the hand pulling path. Dickinson (1996) explained this situation during the stroke reversal in swimming animals: "In order to reverse the sign of circulation and the direction of resultant forces, the biofoil must undergo an extensive rotation during each stroke reversal. The bound circulation of this rotation has the same sign as the previous tranlational circulation, and might possible augment force production during the last portion of each stroke. Once shed, however, the rotational circulation has the same orientation as the stopping vortex of the previous stroke and the starting vortex of the next stroke". This description explains some of the water behaviours described in experimental part of this paper.

Three different vortices can be observed during the propulsion of the hands: starting vortex, tip vortex and hub vortex. The *starting vortex* is produced as it is explained in the figures 6a, 6b, 10a, 10b, 10c, 10d and 14a. In these cases the sweep-back angle is 0º. The starting vortex is generated during all the propulsive movements including all the sweep-back angles (see figure 14b). This vortex is easily visible during suddenly changes of the hand movement direction because the sweep-back angle changes and a new starting vortex is created. The starting vortex after the change of the hand movement direction is detached and it keeps rotating in the water during a short time. The starting vortex can be study on infinite wings or hands, but the swimmer's hand has a finite span. The difference in pressure between upper and lower hand produces vortices that are shed from the hands tips as the water from below tuns upward. These hand-*tip vortices* can be observed during real swimming when the swimmer traps bubbles during the hand entry. A line of bubbles shows the swimmer's pulling path (see figure 11). The *hub vortex* is created in a screw propeller from his centre of rotation. This type of vortex is observed in small propulsive movements of the hands featured during synchronised swimming. This vortex is perpendicular to the propulsive hands (∞) path and created a whirlpool in the water surface. Starting and tip vortices can be observed during the propulsion of the feet in breaststroke as well (see figure. 12).

During flutter kick and underwater undulatory propulsion one different type of vortex is created. Gray (1968) explained the vortices generated by the fishes: "when a flexible undulating body acquires forward momentum, a corresponding amount of backward momentum must be acquired by the water; this backward momentum is concentrated in a vortex wake and appears in the form of a jet of fluid expelled from the wake". The propulsive capabilities of this vortex propulsion can be higher than screw propeller in underwater vehicles. After the down-kick a vortex is generated as described in the figures 13a and 13b. This vortex is the bigger and it is named main vortex. In some cases, we found a small vortex after the upward kick, this vortex is named secondary vortex. This vortex rotates around one horizontal axis perpendicular to the swimmer's displacement.

	**Figure 11:** Tip vortex kept in the water after a freestyle arm pull

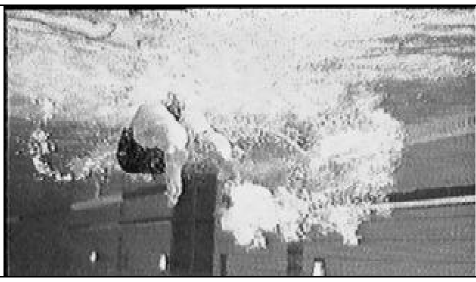
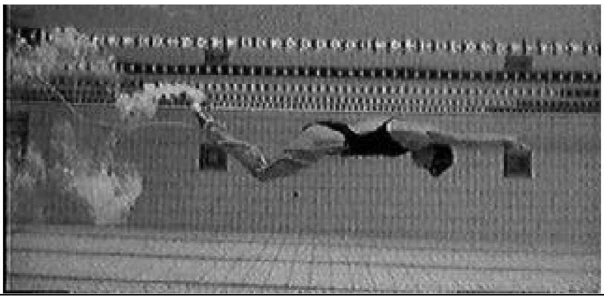


Figure 12: Vortex generated during the breaststroke kick.

Figure 13: Vortices generated during underwater undulatory swimming.

A



B

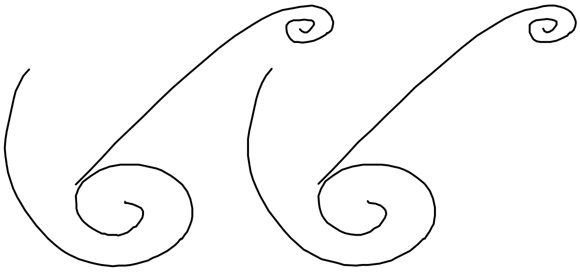
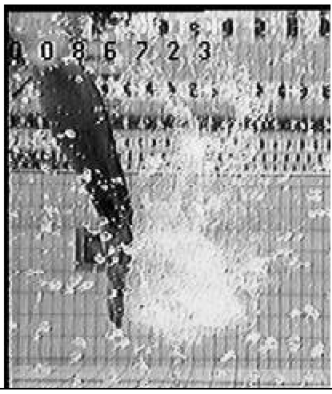


Figure 14: Vortices generated during the end of in-sweep (a) and at the end of the up-sweep (b).

A



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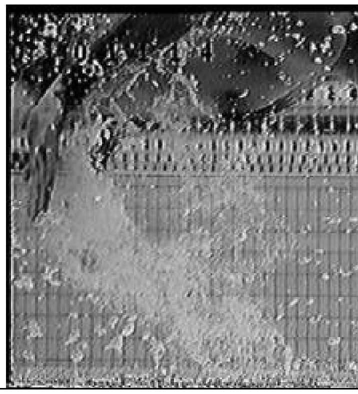

FLOW VISULISATION TECHNIQUES:

Most of the methods used in visualising streamlines require the experimenter to inject some foreign material into the flow that makes the particle, or path, or surface visible. The one major requirement an experimenter must keep in mind is that the material injected should reach the flow velocity as quickly as possible (Granger, 1995). Leonado da Vinci was the first researcher to publish drawings representing observed vortices. The materials used are: dyes, smoke, tufts, small particles, solids, liquids, gas bubbles, air bubbles and optical set-ups. The new computer technologies are letting the researchers make simulations of the flow behaviour around a moving object in a flow (Moin & Kim, 1997). Lists of some research developed about human swimming using flow visualisation techniques are summarised in the next table.

Table 1: Studies developed applying flow visualisation techniques in swimming

Year	Author	Technique utilised
1985	Colwin	Bubbles
1986	Hay & Thayer	Tuft Method
1989	Hay & Thayer	Tuft Method
1992	Colwin	Bubbles
1993	Nakayama	Tuft method
1996	Bixler & Schloder	Computer simulation
1997	Persyn & Colman	Injected dye
1997	Arellano, Gavilán & García	Injected bubbles
1998	Arellano & Redondo	Reflective small particles
1999	Colwin	Bubbles, shadowgram
1999	Arellano	Bubble wall

Our research was oriented during recent years to attempt to visualise the flow during swimming. We developed three different systems to observe vortices: a) vortices generated during undulatory underwater swimming and breaststroke leg kicking injecting bubbles; b) vortices produced by the hand in analytical situation in the lab using reflective small particles and; c) vortices created during analytical situations in the swimming pool and in real freestyle swimming and kicking using a bubble wall.

Experiment 1: Flow visualisation injecting bubbles: A plastic tube was connected from an air compressor to the body of the swimmer until the big toe. The tube diameter was 0.5 cm. The air compressor injected air through the tube and a bubble trace of the big toe trajectory was easily observed during underwater body gliding. Without feet movement and during horizontal gliding, the bubbles draw a line parallel to body displacement until they start going up thanks to the flotation force. This trace was maintained more or less a couple of seconds. When the feet started to flutter kick or breaststroke kick the bubble trace followed the big toe in a laminar path in some phases, but in other phases the bubbles started rotating and kept rotating stationery in the space where they were created and they did not follow the path. We observed during underwater undulatory prone swimming:

- The swimmers generated a big vortex at the end of the downward kick. This vortex started during the initial phase of the downward vertical movement, in the wake behind the feet.
- If the swimmer is kicking from left to right the water rotation is anticlockwise.
- In good swimmers we found the vortex rotated in the same place without displacement, for longer than whit slower swimmers. In some cases the vortex rotated for more than five seconds.
- Some slower swimmers pushed the vortex directly downward.
- We found in some very good swimmers a small vortex at the end of the upward movement rotating clockwise (see fig.13.a) .
- In most cases during the upward movement the bubbles follow a linear path upward and forward similar to the big toe trajectory.
- The previous remarks were observed also in freestyle kicking on the surface with kickboard, in freestyle kicking during full stroke swimming, butterfly kicking on the surface with kickboard, and in butterfly kicking during full stroke swimming. In these cases we videotaped normal swimming without bubble injection. The bubbles were captured by the swimmer from the surface air.

Using the same procedure we had the opportunity to observe a case of an international female champion swimmer practising breaststroke.

- From the lateral view a vortex similar to that created in undulatory kicking was observed but the size was smaller in the same swimmer. From this point of view we saw a small quantity of anticlockwise rotation.
- Observing the breastroke kick from behind a considerable starting vortex was created at the beginning of the downward kick increasing in size until the end of the inward kick.
- At the beginning of the upward kick the vortex kept rotating in the same place and did not follow the feet.
- The axis of this rotating vortex was nearly vertical. Observing the rotation above the rotation was anticlockwise (right foot).

Experiment 2: Flow visualisation using small particles: A small aquarium was utilised in the lab. Small reflective particles were placed in the water with density similar to the water. A big lamp projected light inside the aquarium. The light permitted us to observe easily the position of the water particles. A video camera was placed perpendicular to the aquarium. The shutter speed was low to see easily the path of the particles. The hand made short movements (aprox. 0.30 m) in a rectilinear path. Only attack angles between 40º - 70º were used (see figure 10).

- When the hand started the movement, the thumb being the leading edge (sweep-back angle of 0º), a vortex begun to rotate near the little finger. The water separated near the little finger and returned to the back of the hand over the fingers, creating a vortex.
- When the speed of the hand increased the vortex increased in size and a small vortex was created behind the thumb with opposite rotation to the starting vortex.
- Later the hand suddenly stopped the displacement and the starting vortex kept rotating for a while without horizontal displacement.
- The same situation occurred with a sweep-back angle of 180º.

Experiment 3: Flow visualisation using a bubble wall in analytical situation. A plastic tube, 2 cm diameter, two meters in length and with a line of holes of 2 mm diameter every 5 cm, was connected to an air compressor. The tube was placed in a swimming pool 1.5 m deep, parallel to the water surface, 20 cm in front of an underwater window (4 x 1.5). When the air begun to go up, parallel vertical lines of bubbles (bubble wall) was created moving up with a average speed of 0,68 m/s. A subject located verticaly or horizontaly in front of the underwater window started to make different propulsive movements. When the hand or feet crossed the bubble wall, it was possible to see whether the water was moving or not around the propulsive element.

- Case 1: Long diagonal movements. These movements are similar to those used in freestyle when the pulling path is observed from the bottom. The angle of attack is nearly 50º. We found similar vortices to those created in experiment number two. When this diagonal movement was followed by a sudden change of direction (close to 90º), the previous starting vortex finished its displacement behind the hand and it kept rotating in this position. Immediately, another starting vortex begun rotating in the opposite direction and following the new displacement of the hand.
- Case 2: Rectilinear movements with an angle of attack of 90º. A big wake followed the hand. A vortex street was created and perpendicular oscillations to the hand displacements were observed.
- Case 3: Short-sculling movements similar to those used in synchronised swimming. The situation is similar to case 1, after the sudden change from left to right for example, the starting vortex was detached. The path of tip vortex was observed very clearly and sometimes a vertical whirlpool was created (hub vortex)
- Case 4: Flutter kick: a starting vortex began in the sole of feet during the first part of the down-kick. At the end of the down kick a large vortex was detached. The rotation was anticlockwise if the swimmer was moving from left to right.
- Case 5: Analytical movements related to the breaststroke kick. A clear tip vortex path was shown when the foot was moving with a sweep-back angle of 0º.

Experiment 4: Flow visualisation using a bubble wall in real freestyle swimming: The system used was the same as in experiment 3 but positioned in the middle of the pool lane nearest to the underwater window. Many trials were necessary to get the movement of hand crossing the bubble wall in the correct moment to show a vortex.

- Case 1: Initial down-sweep of freestyle pulling. One small starting vortex was generated during this phase. This vortex was clearly observed when the hand changed from down-sweep (with a small out-sweep component) to in-sweep. The rotation axis of this vortex was nearly horizontal at the beginning, it finished this phase with the axis more horizontal.
- Case 2: In-sweep of freestyle pulling. A bigger starting vortex was observed. The starting vortex in this phase was similar to that shown in the figure 6.a. The axis of rotation is nearly vertical in this phase.
- Case 3: Up-sweep of freestyle pulling. After finishing the in-sweep the swimmer changed the direction of the hand and started a nearly horizontal out and backward sweep. A small vortex was observed in this moment. When the hand started to move upward the biggest vortex of the pull was observed. The axis of this vortex was horizontal.

CONCLUSIONS:

The flow behaviour observed during the different experiments agrees with the general theories of flow dynamics. The several propulsive movements analysed (arm pulls and leg kicks) generated large or starting vortices during linear movements that agree with the theories of steady or quasi-steady flow conditions. When the hands or feet accelerated or changed the direction suddenly the vortex was detached and theories of unsteady flows explain better this situation.

At this moment, it is difficult to state teaching cues for the swimmer and coach. It does not seem correct to tell swimmers things like “try to rotate the water”, because water rotation is produced automatically in a correct propulsion. Besides, it is not possible to feel the water rotations because the flow movement occurs an instant after the hand passes through the water volume. Only in straight hand movements with attack angles of 90º are the vibrations felt which are produced by a vortex street. What does the swimmer feel? The answer is pressure and differential pressure. The swimmer can not feel the differences between lift or drag forces, the swimmers feel only the resultant force. This is a complex perceptive situation, where the swimmer receives information through the tactile and pressure sensitive cells and, kinaesthetic propioceptive system of the pressure drag, skin friction drag, circulation, wake lower pressure and so on. All this means that some swimmers can apply their propulsive force better controlling the direction of the resultant force (as parallel as possible to swimmer’s body displacement: neat effective propulsion). This propulsive feeling is mixed with the perception of the total body drag in each phase that makes the situation much more complex. The problem is to be able to feel the difference between pushing water and applying effective force.

Some situations observed in our experiments such as keeping the vortex rotating stationary after the kick and to develop larger vortices during the hand pull seem related to higher propulsion. Incorrect propulsive movements are when the vortex is pushed away after the kick or when the vortex is small especially during the up-sweep.

Swimmers, especially the beginners, have to play with water trying to feel the water movements. Cues, as proposed by Colwin (1992,1999), seem the most logical way to improve the generic swimming propulsion. However, after all our work, there still seem to be more questions than answers when trying to understand swimming propulsion.

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