Biomechanical Bases

Introduction

In this course, we will address the biomechanical principles related to swimming to better understand the forces acting on a swimmer and the hydrodynamic laws governing their movement, considering the specific characteristics and constraints of the aquatic environment.

The forward movement of a swimmer results from several forces, the first of which is propulsion (locomotor actions that interact with resistance to gain leverage on the water). Particular attention will be given to the various theories and models of propulsion. The second force is resistance to motion (opposing reactions that act against forward movement), and we will present its different types. A third force, related to body positioning as well as propulsive or non-propulsive segments, is lift, which indirectly affects the other two forces. These factors have fundamentally different roles depending on whether the biomechanical principles are associated with Newton's Third Law or Bernoulli's principle.

The importance of this course is clear: to improve, a swimmer must reduce negative resistances while increasing resistances that act in the direction of movement. To achieve optimal swimming efficiency, the swimmer must constantly seek a favorable penetration and forward profile adapted to hydrodynamic laws. Simply turning the arms faster will not make a swimmer go faster.

2.1. Buoyancy

2.1.1 Definition of Buoyancy

Buoyancy is a form of static equilibrium in water, in which part of the body is submerged while another part is above water. In humans, this equilibrium is vertical. The emerged part is generally limited to some portion of the head, while most of the body volume remains submerged (Chollet, 1997, p. 22).

In water, humans are not in their natural element and encounter difficulties adapting. Their buoyancy, as well as their ability to maintain a horizontal position, affects swimming technique and performance (Pedrolletti, 2000, p. 15).

2.1.2 Forces Acting on a Swimmer

At the water surface, a person is subjected to gravity, which acts downward, and to Archimedes' buoyant force, which pushes upward (Boullé-Giammatteï, 2010, p. 20).

A body in water is influenced by several forces:

- Weight (gravity): a vertical downward force applied at the center of gravity. On a solid surface, a body is balanced when the center of gravity projects within the base of support.
- Buoyant force (Archimedes' principle): any body immersed in a fluid experiences an upward force equal to the weight of the displaced fluid, applied at the geometric center of the displaced volume (center of buoyancy) (Chollet, 1997, p. 22).

2.1.3 Swimmer's Buoyancy

Human buoyancy depends on the relative densities of the water and the body. One floats better in saltwater (density ≈ 1.025 at 15°C) than in freshwater (≈ 0.997 at 25°C).

Human body density is the ratio of weight to volume. Heavier bones and muscles, or lower lung capacity, reduce buoyancy. Most people float during forced inspiration, but anthropometric characteristics affect how well they float (Pelayo & al., 2000, p. 229).

If gravity exceeds Archimedes' force, the body sinks; if the opposite, it stays at the surface. Some people struggle to float in freshwater due to high body density, low fat, or high bone density. Lung inflation has a major effect on buoyancy; low buoyancy makes learning to swim more difficult (Grimshaw & Burden, 2010, pp. 278-279).

Because humans have heavy skeletons and muscles, their body density exceeds water, requiring strategies to stay afloat: lung inflation, pressing down on water, or active swimming to counter excess weight.

Without movement, the simplest way to change body density is to inflate or deflate the lungs. If density exceeds water (lungs empty), we sink; if lower (lungs filled), we float.

Water is favorable for movement: apparent weight is null (with positive buoyancy), so the swimmer only opposes forward resistance. Water is ~800 times denser than air, but with a streamlined, floating body, swimming is more energy-efficient per kg per distance than moving on land (Boullé-Giammatteï, 2010, p. 20).

Buoyancy depends on bone mass (density 1.8 N/dm^3), muscle mass (1.05), and fat (0.95). Women (23% body fat) float better than men (15%) (Pelayo et al., 2000, p. 229; Leblanc et al., 2010, p. 153).

Chollet (1997, pp. 23-24) notes that body volume can be measured by displaced water volume. Simple methods involve water level measurements before and after immersion.

Three main techniques assess buoyancy during inspiration:

1. Measure underwater weight of the submerged subject.
2. Add weight to a floating, compact body until full submersion.
3. Anatomical marker method: subject maintains vertical static balance, arms along the body, head horizontal. Water level indicates buoyancy: low (up to forehead), medium (eyes), good (chin) (Cazorla, 1993, p. 101).

Individual differences are large, influenced by age and sex. All buoyancy tests are done in forced inspiration; in expiration, all humans sink.

2.2. Aquatic Balance

2.2.1 Swimming Balance

According to Didier Chollet, aquatic balance corresponds to a state of rest of the human body subjected to gravitational forces that are balanced by buoyant forces (Archimedes' thrust). This state of rest highlights the static nature of balance (Chollet, 1997, p. 26).

Swimming balance requires the body to be in a horizontal position.

- **Buoyancy** in humans corresponds to a static vertical balance.
- **Aquatic balance** corresponds to a static horizontal position.
- **Aquatic equilibration** corresponds to a dynamic horizontal state.

With regard to balance, three types can be distinguished:

- **Stable balance**: the system remains in the position in which it is released;
- **Unstable balance**: the body position changes in order to reach a stable equilibrium;
- **Neutral (indifferent) balance**: regardless of the initial orientation of the body, this orientation is maintained (Chollet, 1997, p. 26).

2.2.2 The Righting Moment

The legs are relatively heavy and have a smaller volume compared to the lungs, which are much lighter and larger in volume.

- The swimmer's center of gravity is therefore located closer to the legs,
- while the center of buoyancy (center of volume) is located higher, around the abdomen or lower chest;
- the center of gravity is generally situated at the level of the pelvis;
- the center of buoyancy is situated higher, toward the abdomen or lower chest.

As a result, the centers of gravity and buoyancy do not coincide; they are located at different vertical levels.

Consequently, the legs tend to sink while the chest tends to float. When lying at the surface of the water, the body is in an unstable equilibrium.

Two opposing forces gravity and buoyant force act on the body at different points of application. This creates a righting moment, which tends to restore the body to a stable equilibrium by aligning the points of application of gravitational force and buoyant force along the same vertical axis.

During swimming, in a dynamic context, the arms when extended forward:

- play an important role in bringing the points of application of gravity and buoyancy closer together;
- thereby facilitate a more stable horizontal body position in the water (Pedroletti, 2009, pp. 64–65).

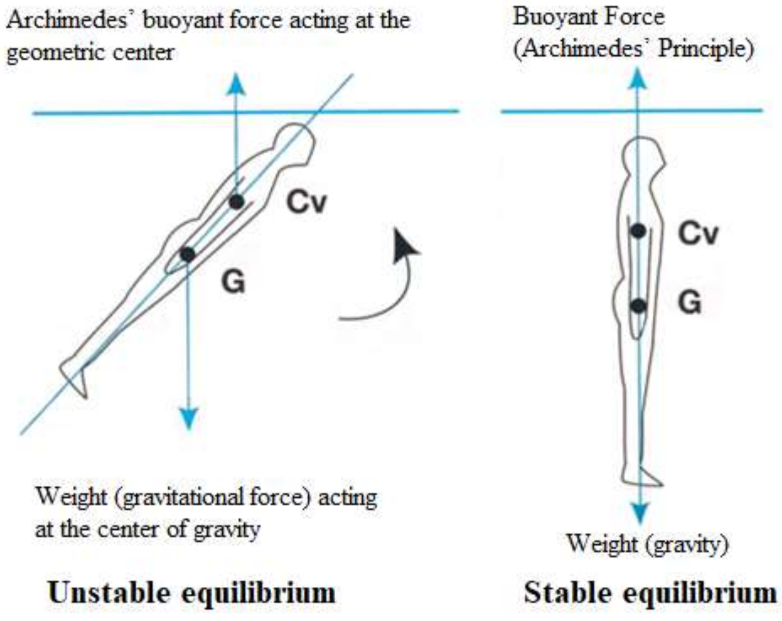


Figure 2: Righting Moment (Pedroletti, 2009, p. 65)

2.2.3 Swimmer’s Balance Level

A static balance test can be implemented with swimmers. It consists of evaluating the time interval between the moment when the subject is in a horizontal static balance and the moment when they reach a vertical balance. The longer this time interval, the better the swimmer’s horizontal balance.

It can be observed that the initial phase of imbalance is the longest; once the righting process is initiated, the return to vertical position occurs more rapidly when the head is in a raised position or when the body is already initially inclined.

It is important to clearly emphasize that the search for horizontal balance is a necessity for any individual who wishes to swim efficiently, insofar as this position is the only equilibrium position that limits resistance to forward motion during displacement. However, this horizontal balance must be constructed, as it results from specific voluntary actions (Clarys & Jiskoot, 1978, p. 71).

2.2.4 Head Positioning and Aquatic Balance

Head position can also have a significant influence on maintaining good horizontal stability. One of the first actions required to achieve horizontal balance is tilting the head in order to align the body segments horizontally. This tilting action also helps manage the emerged body volume so that it is distributed as centrally as possible relative to the entire body. Conversely, raising the head accelerates the process of vertical righting.

In the case of prone balance, this head tilting has consequences for breathing, as the airways then become submerged. The issue of sustained static balance can only be resolved through a dorsal balance position commonly referred to as *“the float”* which allows the airways to remain above the water surface.

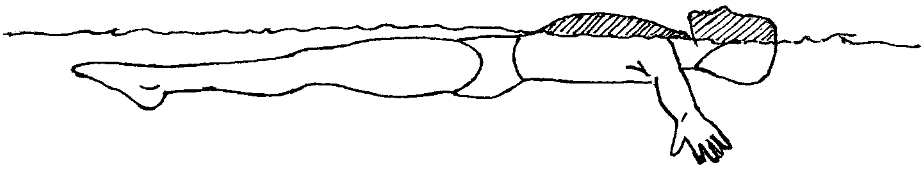


Figure 3: Dorsal Balance

The head is nevertheless maintained in horizontal alignment; the occipital region is clearly submerged, and the external ears are underwater. In the case of dorsal balance, another source of imbalance may occur: lateral rotation. To avoid or reduce this, the appropriate arm position is lateral abduction, with the arms spread outward (Chollet, 1997, pp. 28–29).

2.3 Swimmer’s Equilibration

2.3.1 Concept of Equilibration

Any movement or displacement represents a transient state of imbalance that must be continuously restored. Bipedal posture requires maintaining balance under static or dynamic conditions across highly variable support situations.

In posturology, the term *“static balance”* is often used despite its mechanical inaccuracy. This terminology is commonly employed in the literature to distinguish situations in which the body is voluntarily moving from those in which it is subjected to external perturbations. When a body is in motion, it is therefore in a state of transient imbalance. This is referred to as *dynamic balance*. Human equilibration is thus a process of continuous balance restoration (Paillard, 2016, p. 1).

Unlike balance, which is a concept with a static character, equilibration is inherently a dynamic notion. According to Gribenski (1980, cited by D. Chollet), *"It is the function by which humans maintain their balance at all times."* This dynamic concept may therefore aim at the recovery of a disrupted balance and thus represents an active re-equilibration function.

Because the aquatic environment is a specific medium without fixed support points and due to the deformable nature of the human body, the equilibration function becomes essential. Consequently, when swimming, individuals are constantly recovering from imbalances (Chollet, 1997, p. 32).

The practice of physical and sporting activities modifies the sensorimotor strategies involved in the equilibration function; however, these modifications differ according to the specific demands of each sport.

2.3.2 Relationship Between Equilibration and Breathing

One of the first static imbalances is related to inhalation. The duration of ventral balance depends on the subject's respiratory capacity. When the head is submerged, inhalation is temporarily prevented. The inspiratory phase, which involves lifting the head, disrupts body alignment and horizontal positioning.

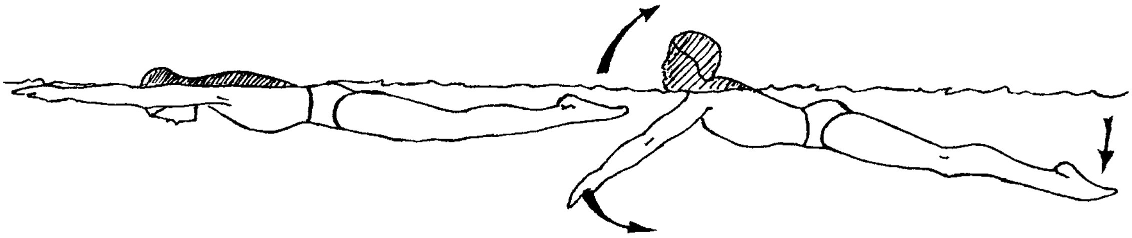


Figure No. 4: Righting movements related to information intake

Each inhalation must therefore be followed by an active movement of head flexion that restores the balance temporarily disrupted, while seeking to correctly reposition the body segments mobilized during this respiratory phase.

Moreover, breathing except in the case of backstroke, where the airways are above water constitutes a major disturbing factor of balance. A contradiction thus appears: the more one breathes, the more swimming balance is disrupted due to changes in head position; but the more effectively one breathes, the more oxygen is supplied to the muscles involved in the action, allowing them to function at maximum efficiency. This shows that breathing should not be left to chance but organized according to a certain number of factors. The number of inhalations over a distance must be optimal; that is, it must allow a sufficient oxygen supply while disturbing the body as little as possible. This implies the effectiveness of each breathing cycle, in which inhalation must be as complete as possible.

One aspect highlighting the importance of reducing inhalation time is directly related to balance: to create the least disturbance, inhalation should be very brief. This action aims to limit, in time, the reduction of buoyant force (Archimedes' thrust) and the dynamic imbalance caused by lifting part or all of the head out of the water. Furthermore, the moment chosen to perform this inhalation should not be left to chance; it should occur at the end of a propulsive path, regardless of the swimming stroke (Chollet et al., 1997, p. 170).

2.3.3 Relationship between balance control and information intake

Information intake in the aquatic environment is quite specific compared to usual actions. Due to the immersion of the eyes in water, the quality of visual information intake is reduced (or even completely eliminated in the case of beginners who close their eyes), insofar as the eye is in direct contact with water, allowing only blurred visual perceptions. The swimmer must therefore rely on indirect cues (for example, a swimmer moving forward looks downward at a 90-degree angle to observe the lines on the bottom of the pool, designed to inform them of their position within the pool space).

What organizes the swimmer is the informational function, with a constant search for visual references, which may conflict with maintaining the "shoulders–head" block and head immersion. At this stage, the teacher should not focus on what the swimmer sees; instead, swimmers often display disorganized breathing, favoring long apnea phases interrupted by expiration and inspiration performed with the face completely out of the water. The problem is not respiratory in nature; it is postural and informational (Arieu & Dupouy, 2008, p. 28).

This visual information intake nevertheless poses several problems related to balance control: it is particularly observed among beginner swimmers, but also at the subsequent stage, that lifting the head out of the water—thus disturbing balance is not due solely to inhalation, but also, and in some cases primarily, to the act of seeking visual information. This information intake then becomes another source of imbalance.

2.3.4 Relationship between balance control and propulsion

Another rebalancing action is associated with both the destabilizing and rebalancing consequences of body displacement in the aquatic environment. Experience shows that a flag falling without wind collapses, but remains upright when wind blows. The same occurs when the flag is moved at high speed even without wind.

When stationary, a swimmer's feet tend to sink. Conversely, when the swimmer is pulled forward, they experience water resistance that tends to lift the lower limbs. This forward propulsion may result from external traction (e.g., a pole pulled from the poolside by a lifeguard), but it can also be generated by propulsive actions of the upper limbs. Additionally, the speed of the body that raises the lower limbs may result from a dive or a push-off from the wall forward; this is known as the prone glide, an action in which balance is facilitated by an active contribution of the water (Chollet, 1997, pp. 30–34).

2.3.5 Balance control and resistance to forward motion

Rebalancing mechanisms are also closely linked to reducing resistance to forward motion. A balanced body using supports in the water moves in the opposite direction of its supports: if it pushes downward, it tends to rise relative to the water level; however, buoyant force then decreases since part of the body emerges from the water, which significantly limits this action. In the case of a backward push, the body advances, and the limitation will depend on the force exerted relative to the body's resistance to forward motion.

A very important link appears between balance and displacement: to move at the same speed, an individual with better balance will expend less energy than another; they will therefore be able to swim longer, and if they have the same propulsion, better balance will allow them to swim faster. To increase speed, a swimmer may choose to reduce resistance to forward motion, increase effective propulsion, or use a combination of both factors (Schleihauf, 1974, p. 94).

Thus, it appears that in front crawl, the lower limbs play an essential role in balance control. At high swimming speeds, it has been demonstrated that the leg kick has little or no propulsive effect; instead, swimmers use leg actions to restore balance in the three planes of space. First, to raise the feet toward the surface (reduction of pitch). Second, to prevent lateral oscillations caused by alternating arm movements (reduction of yaw). Third, to reduce longitudinal roll linked to the immersion of one propulsive arm and the aerial recovery of the other.

These examples clearly show that physical laws and their practical consequences are not the same in static and dynamic conditions, and that numerous paradoxes complicate the analysis of swimming activity.

If swimming is considered a complex task, it can be subdivided into subtasks: balancing, organizing oneself in relation to encountered resistances, ensuring respiratory exchanges, gathering information to orient and move, and thus to propel oneself. The traditional notion of swimmer balance is most often represented by a particular moment in the synchronization of limb motor actions and is expressed by a general body extension in an orientation close to horizontal. In reality, the problem of balance is more complex and integrates data from statics and dynamics, conscious and unconscious aspects, and opposing mechanisms (Catteau & Garoff, 1986, p. 65).

The reference posture must be streamlined, toned, and aligned. This allows the swimmer to reduce resistance to forward motion, achieve economical swimming, and perceive the first sensations associated with moving through a fluid medium. In this posture, following head tilt, vision is oriented vertically. This modification of visual information requires the swimmer to reconstruct spatial orientation based on indirect reading of pool-bottom markers and new tactile and proprioceptive cues (Arieu & Dupouy, 2008, p. 28).

Study shows that body balance is hierarchically and chronologically the first motor problem to be solved. However, from the perspective of effective aquatic movement, it cannot remain isolated for long from the other factors of swimming (Chollet, 1997, p. 36).

2.4 Resistance to Forward Motion

2.4.1 Differentiation between resistance to forward motion and propulsive resistance

Mechanical and biomechanical concepts and notions have evolved over time thanks to advances in scientific knowledge. According to Chollet (1997, p. 48), resistance to forward motion should not be confused with propulsive resistance. Lift forces are fundamentally different from drag forces. It is also necessary to distinguish between wave resistance, friction resistance, and eddy (wake) resistance, just as it is important to differentiate between form drag, wave drag, and friction drag.

Drag is a force generated by the relative motion of a body in a fluid. This force is directed opposite to the body's displacement and is referred to as hydrodynamic resistance when the fluid is water. Drag depends on the drag coefficient (representing the streamlining of the body), the density of the fluid, the area of the body's cross-section, and the square of the velocity (Grimshaw & Burden, 2010, p. 276).A swimmer in motion is a system that creates zones of resistance, which tend to slow down their action. The forward progression of the swimmer's body results from several forces:

- **Propulsion**: locomotor actions that seek resistance in order to establish supports against the water.

- **Resistance to forward motion**: braking reactions that occur on all areas moving more slowly than the propulsive supports.
- **Lift**: related to body positioning as well as to propulsive or non-propulsive segments. Lift has indirect implications for the other two forces.

The laws of fluid mechanics governing resistance are the same whether the body moves through a volume of still water or remains stationary in a moving water current under identical speed conditions. This form of resistance (in both cases) is referred to as passive resistance; it can be measured, for example, by towing an immobile swimmer through the water. Active resistance, on the other hand, corresponds to that experienced by a swimmer during actual swimming, that is, while performing propulsive motor actions (Chollet, 1997, pp. 48–49).

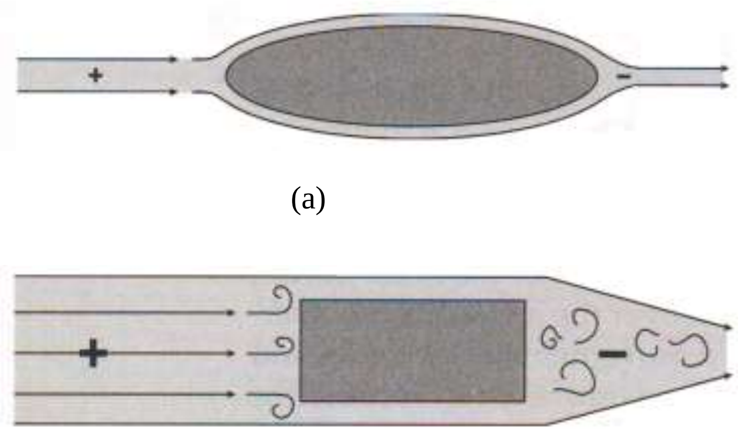
According to Costill et al. (1994, p. 43), water offers resistance to the swimmer’s movement. To reduce this resistance as much as possible, swimmers should seek the most elongated position possible. The continuity of motor actions and aerial recoveries makes front crawl the fastest stroke. In breaststroke, resistance to forward motion is high due to underwater recoveries and the discontinuous nature of propulsion. The reduction of resistance to forward motion is not the same for beginners and expert swimmers. Beginners tend to adopt an oblique position in the water and aim to reduce resistance by seeking horizontal balance without prioritizing speed. Expert swimmers, already in horizontal balance, aim to reduce braking resistance while increasing swimming speed.

2.4.2 The different types of resistance to forward motion in water

A swimmer in motion is subjected to three forms of resistance in water:

2.4.2.1 Form resistance or form drag

A streamlined shape produces the least drag in water. The two objects represented in this figure have exactly the same maximum cross-sectional area but do not have the same shape; therefore, they do not offer the same resistance to forward motion. In Figure No. 5, object (a) has a suitable shape for moving through water: it is streamlined at both ends. In contrast, the shape of object (b) is unsuitable, as it has too many squared edges that interrupt the flow of water toward the rear (Maglischo, 2003, p. 54).



(a)

(b)

Figure No. 5: Representation of resistance to forward motion differentiated by shape
(Ernest W. Maglischo, 2003, p. 54)

Form drag is the resistance that results from the shape of an object moving through water. Reducing the frontal area opposing the movement of water makes it possible to decrease this type of resistance. Therefore, the body should always be kept as close as possible to a horizontal balance, maintained in an elongated and aligned position, and unnecessary movements should be eliminated (Hines, 2000, p. 30).

Unfortunately, swimmers' bodies cannot remain in a static position while swimming. They constantly change position and present a wide variety of orientations to the water they move through. Compared with slower swimmers, faster swimmers maintain the most streamlined shape possible while changing position (Costill et al., 1994, pp. 44 - 45).

Form resistance therefore depends on the shape of the swimmer's body as it moves through the water and corresponds to resistance to forward motion linked to vertical or lateral movements, which increase the frontal surface area (frontal resistance, thus related to the maximum cross-sectional area and body shape), as well as the posterior surfaces that negatively affect suction (wake drag or posterior vortex drag, also known as tail suction) (Chollet, 1997, p. 53).

Moreover, a glide with the arms extended in line with the body allows a greater distance to be covered than a glide with the arms along the thighs. Indeed, body length also influences resistance to forward motion: the more elongated a body is, the lower the resistance. Ungerechts and Niklas (1994) show that at the same speed, passive resistance decreases progressively as the object becomes more elongated.

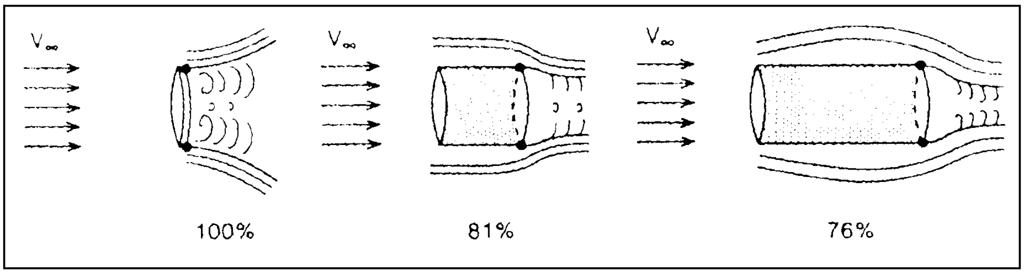
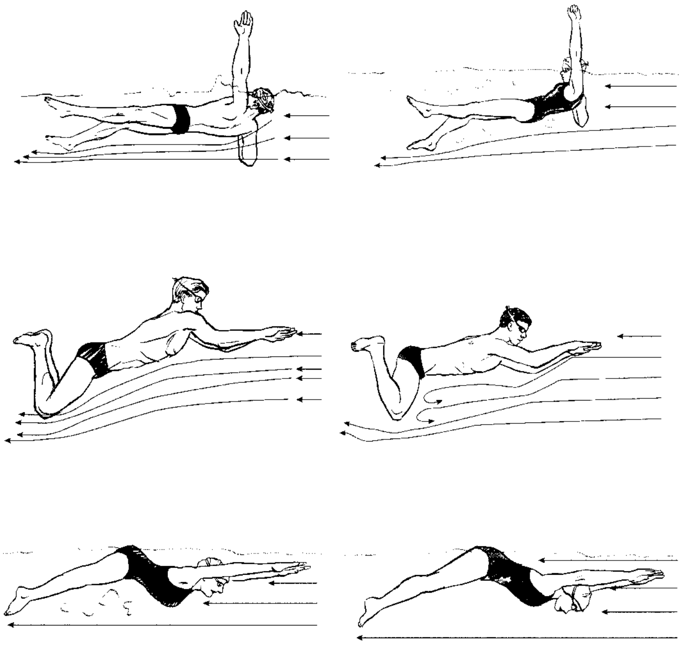


Figure No. 6: Reduction of passive resistance as the length of a solid increases, for the same maximum cross-sectional area and at the same speed
(Ungerechts & Niklas, 1994, p. 138)

Thus, the swimmer seeks to minimize the space they occupy by remaining as horizontal as possible. The body must be oriented so that all its contours progressively taper toward the rear, while presenting the smallest possible surface area to the water in front. The swimmer must find a compromise when striking the water with the feet: deep enough to propel the body forward, but not so deep as to increase form drag beyond what is strictly necessary. The body should not twist excessively from side to side. Finally, the swimmer must be aware of maintaining good horizontal alignment in all swimming strokes, and good lateral alignment in front crawl and backstroke (Costill et al., 1994, p. 46).

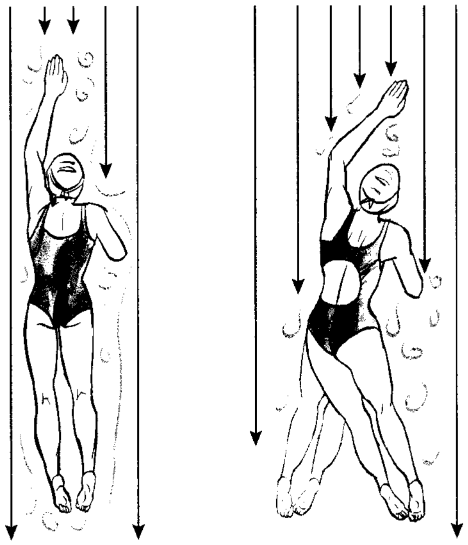
The following diagrams highlight the differences between good and poor horizontal alignment in three of the four swimming techniques (Figure No. 7).



(a) Good body alignment (b) Poor body alignment

Figure No. 7: Comparison between good and poor body positions in three of the four swimming strokes *(Ernest W. Maglischo, 2003, p. 52)*

Moreover, excessive side-to-side body movements can disrupt lateral alignment in the front crawl and backstroke techniques. Figure No. 8 shows a top view of front crawl swimmers. The swimmer on the left is well streamlined, whereas the swimmer on the right twists excessively from side to side. This swimmer inserts her hand into the water across the body's midline, which causes an outward movement of the hip behind the arm and a lateral movement of the legs in the opposite direction. These lateral swinging movements increase turbulence around the body (Costill et al., 1994, pp. 46–48).



(a) (b)

Figure No. 8: Effects of good and poor lateral alignment in front crawl *(Ernest W. Maglischo, 2003, p. 53)*

2.4.2.2 Wave resistance or wave drag

The body fights wave drag by creating a wake, just like boats do. To move forward at the surface, it must push water out of its path by forming a wave. The creation of this wave requires energy, all of which is supplied by the swimmer, and the amount depends largely on the distance the water must travel to move away from the path described by the body. The wider the path the swimmer opens at the surface, the larger the wave and the greater the energy expenditure required to overcome wave drag (Hines, 2000, pp. 30–31).

When a body moves at the surface of a liquid, a turbulent zone is created, producing waves, the most significant of which are the bow wave at the front of the body and the stern wave at the rear. Like all forms of resistance, wave drag depends among other factors on the swimmer's speed and body shape, and it is directly linked to movements performed near the water surface.

Waves and water turbulence create a high-pressure zone that acts as a major brake on the swimmer's forward motion. Some external waves affecting the swimmer can be reduced through the use of "anti-wave lanes," but it is mainly the waves caused by poor body positioning or poor water entry that limit propulsive efficiency. The movements that contribute most to wave creation are vertical movements upward and downward especially when they occur close to the water surface. These most often correspond to the phases of water entry and exit of the propulsive segments (Chollet, 1997, p. 55).

These movements create arcing waves that press against the swimmer's body and slow their speed. Such arcing waves are generated by the swimmer's head and trunk when they move forward, sideways, or upward and downward. They are also produced by the recovery movements of the arms and legs. The limbs push forward against the water, creating turbulence that increases pressure at the front of the body and secondarily produces a backward-directed force that rapidly and significantly slows the swimmer's speed (Costill et al., 1994, p. 48).

2.4.2.3 Friction resistance or skin drag

Friction drag is caused by the friction of a body moving through water. This type of resistance cannot be reduced through technique, but rather through preparation and equipment. Properly fitted swimsuits and swim caps help achieve this goal. Friction drag can also be reduced by wearing competition swimsuits made from advanced technological materials designed to limit water absorption (Hines, 2000, p. 31).

When a body moves through a fluid, the fluid molecules closest to the body adhere to it. As these molecules move away from the body surface, their velocity changes and, beyond a certain distance, matches the velocity of the fluid in the outer flow around the body. The thin layer of fluid in which this velocity gradient occurs is called the boundary layer. Because these adjacent layers of fluid have different velocities, significant viscous forces are generated (Chollet, 1997, p. 55).

According to Costill et al. (1994, pp. 43-49), the main factors influencing the magnitude of friction drag experienced by swimmers are their frictional surface area, their speed, and the roughness of their body surface. Swimmers cannot influence their body surface area, and they can only affect their speed by choosing the appropriate pace in the early part of the race. This means that the only significant way to reduce friction drag is to smooth the friction surface. Smooth surfaces clearly generate less friction than rough surfaces, which explains why some swimmers shave before major competitions.

Drag resistance is linked to changes in water flow around the swimmer. Flow can be either laminar or turbulent. In laminar flow, water molecules move in linear, homogeneous streams. This type of flow produces little resistance, as water molecules slide smoothly along the flow layers without disturbance. When these laminar flows encounter an obstacle, such as a swimmer's body, the molecules are redistributed unevenly in all directions, and the flow becomes turbulent.

The molecules bounce in all directions, collide with nearby flow lines, making them turbulent as well, and so on. In front of the body, this expanding turbulence creates a high-pressure zone that slows the swimmer. Because the flow lines are completely disrupted, no laminar flow can occur around the immersed body. These flow lines only rejoin far behind the swimmer. A low-pressure vortex zone forms at the rear, creating a suction effect that also slows forward progression. These effects can be observed through the air bubbles underwater that surround the swimmer's segments. Turbulent flow creates vortex currents that hinder the swimmer.

The phenomenon of low pressure and suction behind the body is effectively used in training when a swimmer positions themselves in the wake of another swimmer's kick to benefit from reduced resistance and suction effects.

Thus, the more or less streamlined shape of a body immersed in a fluid is of great importance. Unfortunately, the swimmer's body is not naturally adapted to the aquatic environment. Careful attention must therefore be paid to body position in order to minimize the disadvantages caused by turbulent flow of the various streamlines and by differences between frontal and rear pressure zones.

2.5 Swimmer Propulsion

The swimmer is confronted with a double imperative:

to reduce the resistances to forward motion that oppose displacement, and to increase the propulsive resistances created by the limbs in order to move faster. The swimmer's displacement is therefore conditioned by the creation and maintenance of these propulsive resistances.

Thus, in one case, resistances are the consequence of the action of water on the body and are passively endured by the swimmer. In the other case, the swimmer actively creates these resistances. From a theoretical point of view, these propulsive resistances can be generated according to different biomechanical models with highly variable efficiencies (Toussaint & Beek, 1992, p. 9).

According to Maglischo (2003, pp. 5–12), many theories exist on this subject, but none of them has been definitively proven. Many experts accept Bernoulli's theorem as the basis of propulsion in swimming. Even though it is certainly the most commonly accepted theory today, it is probably not the main physical law that swimmers use to propel their bodies forward. The primary propulsive mechanism used by swimmers is more likely based on Newton's third law.

According to the same author, the main reason Newton's action–reaction law was rejected in favor of Bernoulli's theorem was probably the study by Brown and Counsilman (1971). They showed that swimmers propel themselves more through diagonal movements than through movements directed straight backward, which led researchers to seek another explanation for propulsion in swimming. Unfortunately, Newton's law was misinterpreted by assuming that swimmers had to push directly backward with their arms and legs to push water backward. It was not realized that swimmers can push water backward very effectively even when propelling in diagonal directions.

Swimming displacement is the result of the propulsive action of the legs and arms in the water. The efficiency of displacement depends on the relationship between hydrodynamic laws (Newton’s laws and Bernoulli’s principle) and the coordination of motor actions (Tourny et al., 1994, p. 43).

For their part, Sprigings and Koehler believe that, from a practical point of view, the predictive potential of a model based on Newton’s laws is superior to that of a model based on Bernoulli’s theorem. The main characteristics of lift and drag can be derived using an approximate method based on the application of Newton’s second and third laws rather than Bernoulli’s equation. The advantages of the Newtonian model, compared with the Bernoulli model, are that it can be used to provide both quantitative and qualitative data and that it is intuitively easier to understand, making it possible to derive relatively simple and reasonable equations (Sprigings & Koehler, 1990, p. 244).

2.5.1 Main Theories of Propulsion

2.5.1.1 Propulsion model based on Newton’s third law (action/reaction)

This model is based on the law linking action and reaction, which can be expressed as follows: when swimmers push water backward, they accelerate forward with a force of equal magnitude. In other words, for every action there is an equal and opposite reaction. Consequently, if a swimmer wants to move in a given direction, they must exert a force with their limbs in the opposite direction. For the swimmer, this results in orienting the propulsive surfaces (for example, the hand) perpendicular to the direction of displacement, with the direction of the propulsive forces parallel to the direction of movement (Costill et al., 1994, p. 50).

This search for propulsive action must take into account the specificity of the aquatic environment, namely that water molecules are evasive and that any movement performed perpendicular to the direction of displacement must be carried out with progressive acceleration. This acceleration makes it possible to carry along and push against the same mass of water throughout the entire propulsive path. If the movement is not accelerated but uniform, water molecules will escape behind the hand and propulsion will be very weak or even nonexistent (Arellano et al., 2006, p. 15).

Thus, this model is based on two principles:

- Orientation of the propulsive surfaces perpendicular to the direction of displacement, with the direction of the propulsive forces parallel to the direction of movement;
- Support on a mass of water and progressive acceleration of this support in order to retain this mass of water throughout the entire propulsive movement.

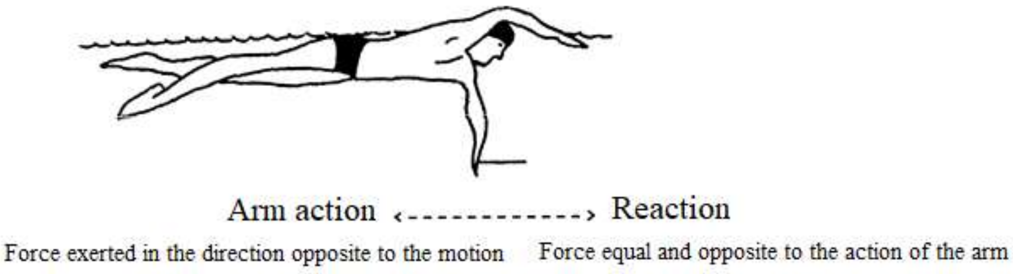


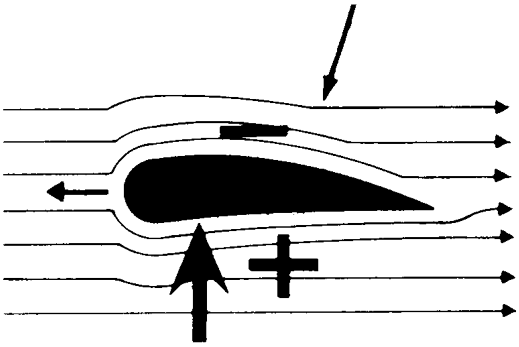
Figure 9: Application of Newton’s Third Law

2.5.1.2 Propulsion Model Based on Bernoulli's Principle

For many years, it was believed that the freestyle swimmer had to pull and then push their hand along a straight trajectory underwater passing beneath the swimmer's center of gravity. This assumption was based on the idea that the swimmer used their hand like an oar, creating a wake behind it. Consequently, applying Newton's third law of action and reaction, if the swimmer wanted to move straight forward, they had to push the water directly backward.

However, underwater footage of elite swimmers demonstrated that their hands followed an S-shaped path, an inverted question mark, or other similar trajectories. Never was a champion observed moving their hand in a straight line (Counsilman, 1986, p. 179).

Bernoulli's principle states that the pressure of a fluid is related to the increase in its flow velocity. For example, airplane wings are designed to be inclined relative to the direction of motion so that air flows much faster over the upper surface of the wing than the lower surface. This difference in airflow velocity results in increased pressure below the wing and decreased pressure above it. The result is lift, or in other words, an upward force acting against the wing (Figure 10).



Water flows faster here, causing a decrease in pressure

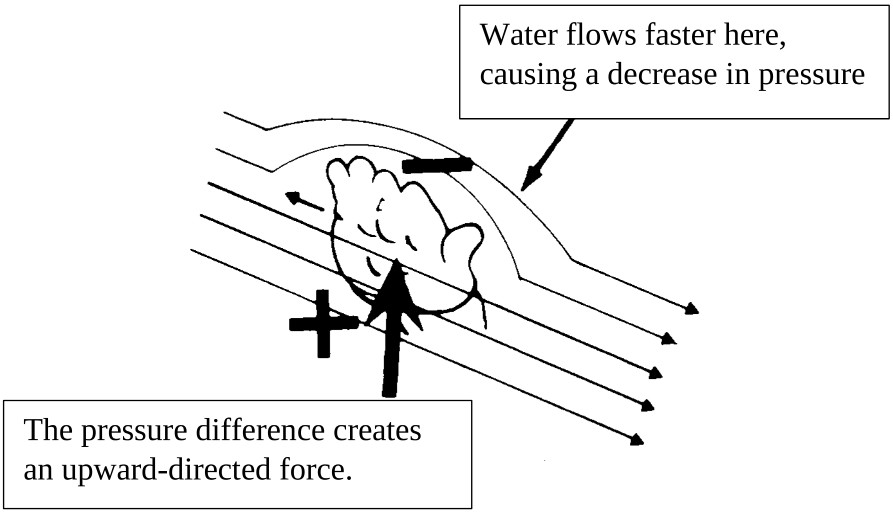
The pressure difference creates an upward-directed force.

Figure 10: Application of Bernoulli's principle on an airplane wing (J.E. Counsilman, 1986, p. 180)

The basis of propulsion, according to Bernoulli's theorem, is that swimmers use their hands like wings. When water flows over them, it moves faster on the dorsal side than underneath on the palmar side. This creates a pressure difference between the palmar and dorsal surfaces, producing a lift force. When this lift combines with the drag force acting on the hand, it generates a resultant force that propels the swimmer's body forward (Toussaint & Beek, 1992, p. 12).

Although it is highly likely that lift and resultant forces are indeed produced when the swimmer pushes diagonally, the magnitude of these forces is probably more related to the swimmer's hand attack angle and the backward displacement of water it generates than to any acceleration of the fluid flow above their dorsal joints. If this were not true, swimmers would not need to orient their hands at different angles while moving; they could simply use their hand like a wing to produce these forces in accordance with Bernoulli's theorem. However, research and individual observations have shown that swimmers generate more force when moving their hands in water using very precise attack angles (Costill et al., 1994, pp. 50-51).

A boat propeller works in a similar way, providing a forward-directed propulsive force. Likewise, a swimmer's hand, if properly angled relative to its trajectory in the water, can act like an airplane wing or a boat propeller, enabling forward propulsion of the swimmer (Figure 11)



Water flows faster here, causing a decrease in pressure

The pressure difference creates an upward-directed force.

.Figure 11: Application of Bernoulli's principle on the swimmer's hand (J.E. Counsilman, 1986, p. 180)

2.5.1.3 Forces Exerted by a Fluid on a Profile

If we consider a fixed obstacle (the swimmer's hand or an airplane wing) and a fluid moving at a constant speed, the resultant force exerted on the swimmer's hand or the wing can be reduced to a single force: F (the hydrodynamic force in water or aerodynamic force in air). This force can be decomposed into two components: a drag force (opposite to the direction of motion) and a perpendicular force: lift.

The hand's angle of inclination is extremely important in producing propulsion by combining drag and lift forces. If the attack angle is too large, the swimmer uses the hand like a paddle rather than a propeller blade. With too little angulation, both lift and drag forces are weak, and the hand simply slips. For the swimmer, this means the hand's orientation must be continuously adjusted with each change in the trajectory of the stroke. The angle of incidence relative to the hand's path can range between 20° and 50° (Morouço et al., 2011, p. 167).

This adjustment is necessary because the hydrodynamic force, composed of drag and lift, determines the intensity and direction of the swimmer's movement. To achieve maximum intensity, the force must be directed forward. Therefore, the swimmer must find an optimal technical finesse based on sensitivity or "feel" for the water.

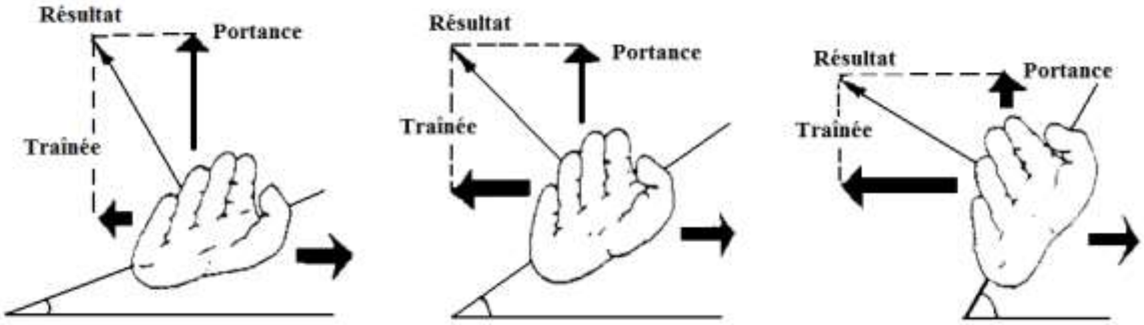


Figure 12: Hand inclination angle contributing to propulsive outcome by combining drag and lift (Colwin, 1982, cited by Chollet, 1997, p. 66)

However, some additional clarifications must be considered: the first concerns the respective directions of lift and drag. A constant relationship exists: lift always acts perpendicular to drag, which is always opposite to the direction of motion.

Two scenarios can occur: when movement is forward, lift is positive, as in an airplane wing; but it is also possible for lift to be negative, for example in an inverted wing or a downward-oriented wing.

- The second clarification: in the case of a swimmer, it is possible to dissociate the direction of the body's movement (forward) from the orientation of the propulsive surfaces (e.g., downward). In this case, if the hand moves along a downward trajectory, the drag will be directed upward, opposite to the motion; then, if the hand's orientation is correct, the lift will be directed forward.

This model is therefore based on two principles:

1. The orientation of the propulsive surfaces (e.g., the hands) should never be strictly perpendicular to the direction of movement, and the direction of the resulting propulsive force is not parallel to the displacement.
2. The swimmer does not push against a single mass of water but on a succession of different water masses. Therefore, the movement is not uniformly accelerated but occurs in a series of accelerations. The rhythm (sequence of stronger and weaker strokes) of the propulsive contacts will thus be variable (Chollet, 1997, p. 66).

Loetz et al. (1988, p. 61) studied the pressure peaks of the hand in all four strokes. They found that in breaststroke, there are two pressure peaks, and in the other three strokes, three pressure peaks. This confirms that elite swimmers rely on different water masses and that the rhythm of propulsive contacts is variable rather than uniformly accelerated.

However, this analysis should be considered cautiously from a learning perspective, as the integration of this technique is largely unconscious. Indeed, many swimmers who are unaware of these principles still compete at a high level. Therefore, this analysis is largely theoretical and difficult to apply directly for performance optimization.

2.5.2 Aquatic Propulsion Models

Six models are presented: four traditional (action/reaction) and two based on lift.

2.5.2.1 Traditional Models of Aquatic Propulsion

2.5.2.1.1 Paddle Wheel Model

Theoretical principle: This is based on Newton's third law, the law of action-reaction.

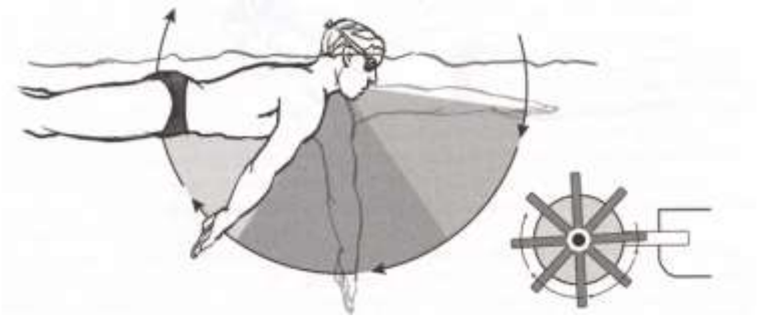


Figure 13: Arm-extended swimming corresponding to the paddle-wheel model (E.W. Maglischo, 2003, p. 7)

Swimming corresponding to this model can be characterized by a propulsive trajectory with arms fully extended. The use of this model in swimming is justified for beginners because it allows better perception of the movement when the arm is extended, as the shoulder proprioceptors are very precise. The negative consequence of this model is the significant strain on the shoulder muscles.

Moreover, while an increase in rotational speed initially improves the swimmer's forward velocity, very quickly this acceleration no longer affects the body's speed (Chollet, 1997, p. 69).

2.5.2.1.2 Rowing Model

This is still based on the action-reaction law, but with an added horizontal linear acceleration.

This acceleration generates support against the moving masses of water, and the reaction is the forward movement of the swimmer's body. Accelerating the propulsive contacts allows the propulsion forces to remain in contact with the fleeing water masses. The shoulder muscles are heavily engaged.

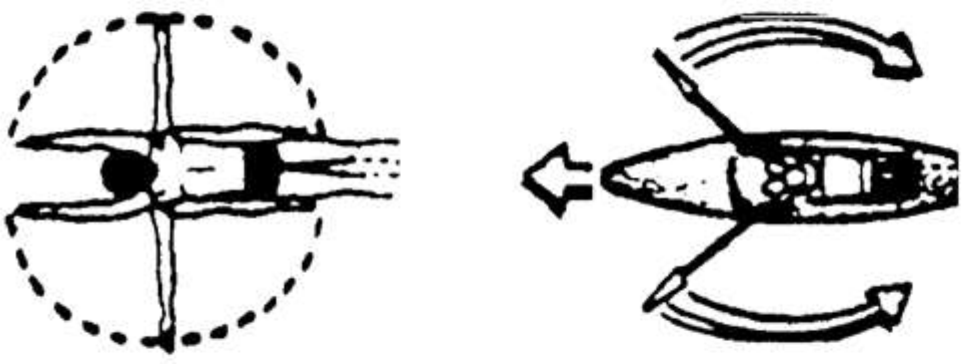


Figure 14: Horizontal arm stroke corresponding to the Rowing model
(According to P. Pelayo et al., 2000, p. 242)

2.5.2.1.3 Paddle Model

The logic of this model is to constantly seek out stationary masses of water and push them backward. A swimmer using this model performs a horizontal arm movement, moving their propulsive contacts in a sinusoidal pattern in order to engage stationary water masses and push them behind.

Figure 15: Swimming following a horizontal sinusoidal trajectory corresponding to the Paddle model
(According to D. Chollet, 1997, p. 72)

There is a pursuit of better efficiency by mobilizing the propulsive surfaces toward stationary water masses (thus creating less “slippery” contacts). However, the trajectory is horizontal, and depth is not utilized (propulsion occurs in 2 dimensions).

2.5.2.1.4 Eskimo Roll Model

In this model, the paddle’s orientation is not only horizontal; the search for stationary water masses occurs in all three planes of space to create propulsive contacts. A swimmer using this model moves their arms in a curved S-shaped path across all three spatial planes.

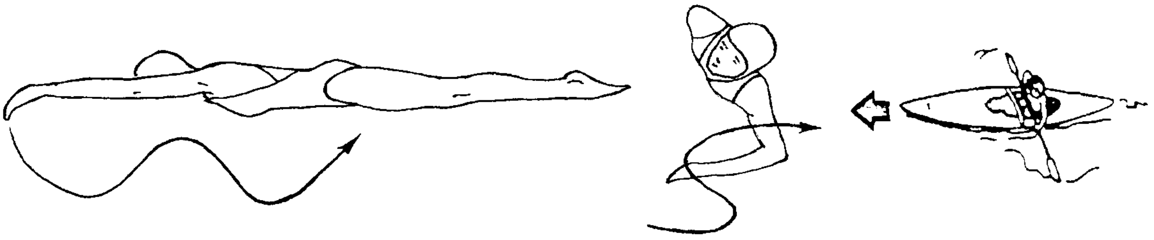


Figure 16: S-shaped hand movement in the 3 planes of space (D. Chollet, 1997, p. 73)

In traditional models of aquatic propulsion, the principle of orienting propulsive surfaces perpendicular to the direction of movement, with propulsive forces aligned parallel to the direction of movement, is fundamental.

Conversely, in lift-based models, the propulsive surface should never be at 90 degrees to the direction of the water flow generated by the push.

2.5.2.2 Models Based on Lift in Aquatic Propulsion

2.5.2.2.1 The Fin Model

In this model, the trajectories are constantly oblique, either with compensation of negative lift by positive lift (as in the dolphin undulation) or with positive lift predominating over negative lift (as in planing or surfing).

Figure 17: Swimming According to the Undulation or Fin Model (P. Pelayo et al., 2000, p. 242)

Two major applications of this model are used: one is the body undulation or leg kick, and the other is the oblique push of the upper limbs.

If undulation is more effective than arm and leg propulsion on the backstroke, this is likely due to the reduction of resistances to forward motion and the use of lift as a source of propulsion. Regulations have limited the use of this type of propulsion in backstroke events.

2.5.2.2.2 The Propeller or Sculling Model

This model is based on Bernoulli’s principle. A propeller is essentially an ordinary screw, and its theory of action is the same. When a propeller rotates quickly in water, the surrounding water is set in motion at the same speed, and due to the reaction it exerts on the inclined surfaces of the propeller, it imparts forward motion to the boat. The faster the propeller spins, the faster the boat moves. The propeller’s rotational movement, even when rapid, is constant; there is no acceleration. Since Bernoulli’s time, the propeller has undergone continuous development, and the current ideal seems to be a variable-pitch propeller that adapts to speed to increase system efficiency.

In 1971, Counsilman, after observing underwater footage of elite swimmers, showed that their hands followed an S-shaped path. He concluded that the swimmer uses the hand like a propeller. Indeed, if the hand is properly angled relative to its trajectory in the water, it can act like a boat propeller and thus provide forward propulsion.

This propeller model has often been used to explain the propulsion logic of expert swimmers. In practice, the sculling model is equally interesting because it closely resembles natural swimming movements while still following the principle of pressure differences.

In a sculling motion that propels a vessel, the paddle is never perpendicular to either the direction of movement or the orientation of the stroke. In synchronized swimming, sculling movements with the hands are common. For example, the “forward” scull performed with the head in a dorsal position (arms along the body) involves the hands rotating (backs of the hands facing the thighs), palms angled toward the pool bottom (wrists flexed 45° upward), maintaining this angle as the forearms move outward simultaneously, then rotating the palms inward against the thighs. (Chollet, 1997, pp. 76-78)

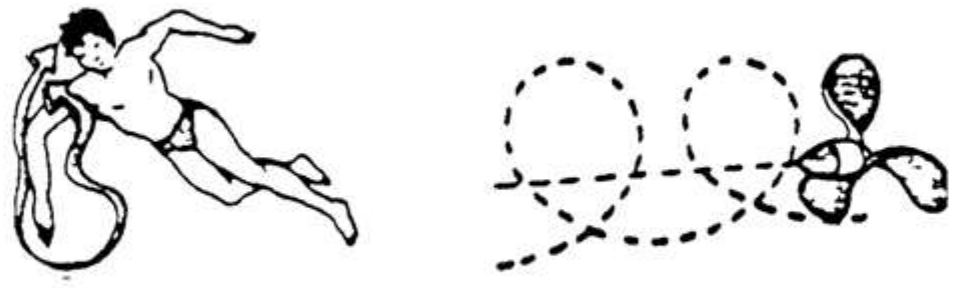


Figure 18: Hand Stroke Path Corresponding to the Propeller Model (D. Cholet, 1997, p. 77)

In competitive swimming (racing), sculling alone cannot provide the swimmer’s full propulsion. Schleihauf (1986, p. 12) specifies that arm propulsion in swimming is derived from the combination of lift and drag forces. Both of these forces dominate at different times within the same stroke cycle. For example, lift forces dominate in breaststroke, while in freestyle, lift and drag forces each dominate in turn during different phases of the stroke.

The closer the hand exits the water to the point where it entered (marked, for example, by a float on the lane line), the greater its efficiency.

J.E. Counsilman (1977) further explains, in relation to the complementarity of lift and drag, that maximum propulsion efficiency in water is achieved by moving a large mass of water backward over a short distance rather than a small amount of water over a longer distance.

2.6 Common Principles Across the Four Competitive Strokes (Counsilman , 1986)

1. The hands do not move through the water in a straight line but follow a sinuous trajectory to push against "more stable" layers of water and to combine different hand angles for the optimal water catch.

2. The swimmer does not "pull and push" with fully extended arms but bends the elbow. This allows the hand to tilt and apply the full force backward.

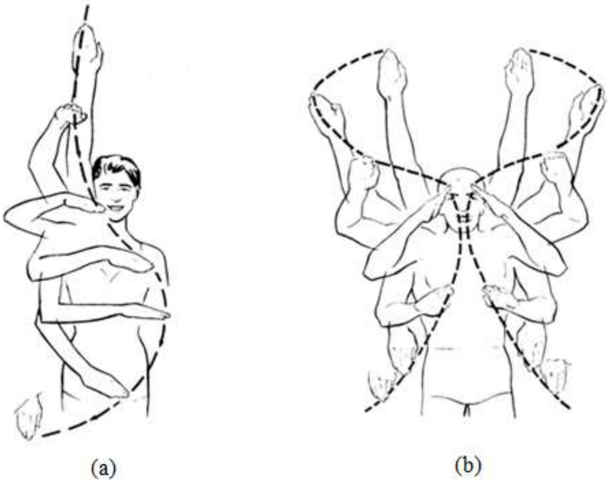


Figure 19: Arm Trajectories in Freestyle (a) and Butterfly (b) (Underview)

3. The elbow must be kept high and forward (or elevated) during the "push" phase.

4. At water entry and exit, the hand must be angled appropriately to minimize the number of air bubbles created. In freestyle entry: lead with the thumb, fingers together, at an angle of 35°–45°; at exit, palm facing the thigh, pinky exiting first.

5. Hands must maintain the correct angle during the arm's pull and push in the water to achieve maximum power (hand angle close to 37° relative to the trajectory).

6. Aim for the best possible hydrodynamic profile by reducing frontal drag and vortex drag (or tail suction).

7. Avoid pushing water back against the body during the stroke, as this increases resistance and slows forward progress. (Counsilman, 1986, pp. 92–100)

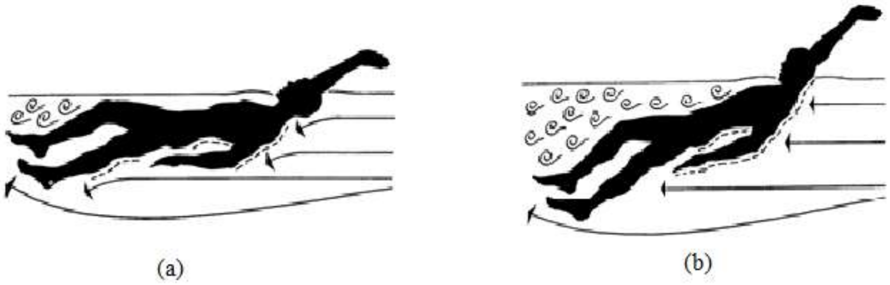


Fig. 20**:** The swimmer (a) generates less frontal and vortical resistance than the swimmer (b).

2.7 Role of the Legs in Propulsion

In most swimming strokes, the arms are the primary source of propulsion. It has long been thought that the flutter kick was not a propulsive element in freestyle, backstroke, and butterfly.

According to Costill et al. (1994, p. 61), the main argument was that swimmers' leg movements in these strokes are not directed backward. Consequently, the leg kick only serves to stabilize the body during the swim. Other arguments indicate that leg kicks consume four times more oxygen than arm movements at the same swimming speed and significantly increase the energetic cost of swimming.

Today, the role of the legs in propulsion is being reconsidered. J.E. Counsilman observed during the qualifications for the 1976 Olympic Games that the majority of 100 m freestyle finalists, both men and women, used a six-beat kick per arm cycle, whereas for the 800 m and 1500 m events, a two-beat kick was more common (Counsilman, 1986, p. 118).

According to Cholet (1997, pp. 95–96), it is reasonable to consider that the longer the distance, the less significant the leg kick is in propulsion. This results from an efficiency issue: at the same speed, the leg kick requires more energy than arm movements. Therefore, in sprint events where maximum propulsion is advantageous (50 m, 100 m), the six-beat kick is primarily used. In endurance events, where energy management is critical (800 m, 1500 m), the two-beat kick is preferred. This is also due to the fact that the velocity produced by propulsive actions is not constant throughout a stroke cycle. Variations in the center-of-gravity velocity during an arm cycle are greater than those produced by a six-beat kick.

Two cases can then be distinguished:

1. **Case 1:** The maximum velocity of the center of gravity remains lower than the minimum velocity produced by the arms. In this case, the legs have no direct propulsive effect. This occurs in middle-distance swimmers, who maintain excellent continuous arm movement while their leg actions are minimally propulsive.
2. **Case 2:** The maximum velocity of the center of gravity exceeds the minimum velocity produced by the arms. In this case, the legs contribute directly to propulsion. This is particularly true for sprint swimmers with effective arm-leg coordination and powerful kicks.

Thus, the propulsive role of the kick is primarily linked to the relative efficiency between leg-only and arm-only propulsion, but it is also influenced by the intermediate "gaps" in the propulsive actions of each arm.