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CURRENT SWIMMING TECHNIQUES: THE PHYSICS OF MOVEMENTS AND OBSERVATIONS OF CHAMPIONS[1]

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The techniques of competitive swimming strokes govern the success of serious swimmers. The concordance of techniques with principles of physics, biomechanics, and marine engineering governs the *propelling efficiency* with which individuals perform. This presentation attempts to cover some basic properties of a science of swimming techniques; at least those properties against which there are no arguments. It is intended to show that there are reasons to do and not to do movements in competitive swimming techniques.

Individual Variation

One frequently hears or reads of the suggestion that swimmers should be taught to swim like a particular champion or role model. Not only is that rife in approaches to conditioning but it is does pervade technique instruction. Hay (1993) warned about the pitfalls of trying to replicate movement images displayed by successful athletes. The idiosyncratic needs of individuals were contained in the *Principle of Individuality* (Rushall & Pyke, 1991), an important factor that pervades coaching in any sport. With regard to technique, champions do exhibit action segments that illustrate the application of a correct movement principle but often only to have other features of their stroking patterns exhibit incorrect segments. To avoid copying poor technique features a coach has to understand movement science and physics principles and then apply them to many varied competitive swimmers. When one considers the differences in lever lengths, the origins and insertions of muscles, the shape of fluid flow about the body, and the actual mind-set that controls the application to swimming techniques, it quickly becomes obvious that no two swimmers should expect to look completely alike when swimming any competitive swimming stroke. Copying the technique of a particular champion swimmer, instead of only the correct features of technique, is perhaps the most common form of developing technique but unfortunately it is wrong.

Understanding the physics, biomechanics, and marine engineering principles that are appropriate for swimming techniques and then applying them effectively is an essential characteristic of correct coaching. The remainder of this presentation will cover some of the more important and basic scientific principles that should be considered when instructing swimming techniques.

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[1] An invited presentation at the 4th Annual Hall of Fame Coaches Clinic, August 28-30, 2013 in Clearwater, Florida.

Newton's Laws Are Always Present

Newton's three laws of motion are always represented in any part of competitive swimming and should be part of any discussion or analysis of swimming techniques.

Newton's First Law. A body remains at rest, or continues to move in a straight line at constant velocity, unless acted upon by a net external force.

This law is most commonly used to explain events that demonstrate a continued state (e.g., a stationary ball on the ground) or a slowly diminishing movement state (e.g., a train coasting on a set of flat tracks). However, what is more useful is to ask the question why an entity is not in a constant state of motion or rest. If that is asked, then the forces that act on a moving object, such as a swimmer, will yield important information about how to modify the motion of such an object to yield a more efficient movement pattern.

In swimming there are forces that accelerate a swimmer, for example the propulsive forces generated by the power-phase in arm strokes, and forces that negatively accelerate a swimmer, for example, resistances and counter-productive movements such as some forms of kicking (see Figure 1 of Ian Thorpe's kick). In competitive swimming, competent performers speed-up and slow-down in a cyclic manner to produce an oscillating form of progression (see Mike Barrowman's acceleration curve in Figure 2). As well, in stages of some strokes there are no obvious forces occurring which is termed an "inertial lag". A common example is in "catch-up" stroking in crawl stroke when one arm is extended forward and the other is recovering. At least in that position no propulsive forces are being developed despite unproductive kicking continuing. The only active force is the enhanced resistance created by kicking which decelerates the swimmer.

Figure 1. Ian Thorpe's kick at the time of breathing to the left. The kick's force has a considerable vertical component and a troubling horizontal component that would slow the swimmer.

What is a desirable conclusion from this interpretation of Newton's First Law is that propulsive forces should be magnified and applied continuously and that resistive forces should be minimized. That would result in a high level of "propelling efficiency".

Newton's Second Law. The acceleration produced by a net external force is: (a) in the direction of the net external force; (b) proportional to the size of the net external force; and (c) inversely proportional to the mass of the body being accelerated.

The major point of this law is that it governs the effects of forces. A force is composed of two factors, mass and acceleration which leads to the simple formula:

Force = mass x acceleration

Competitive swimmers need to apply forces to move forward. The most obvious source of force development would be in the power-phase of all arm strokes and in breaststroke, also the kick. Contrary to established dogma, kicks in the other three strokes are not propulsive and therefore should not be magnified. Kicks should only be strong enough to counterbalance forces not developed in the direction of the intended line of progression. In their purest form, propulsive forces should be straight forward and horizontal. However, since humans are very imperfect aquatic machines, some forces are developed that have a large lateral or vertical force component. When that occurs, the horizontal force component needs to be as large as possible and in the direction of intended progression.

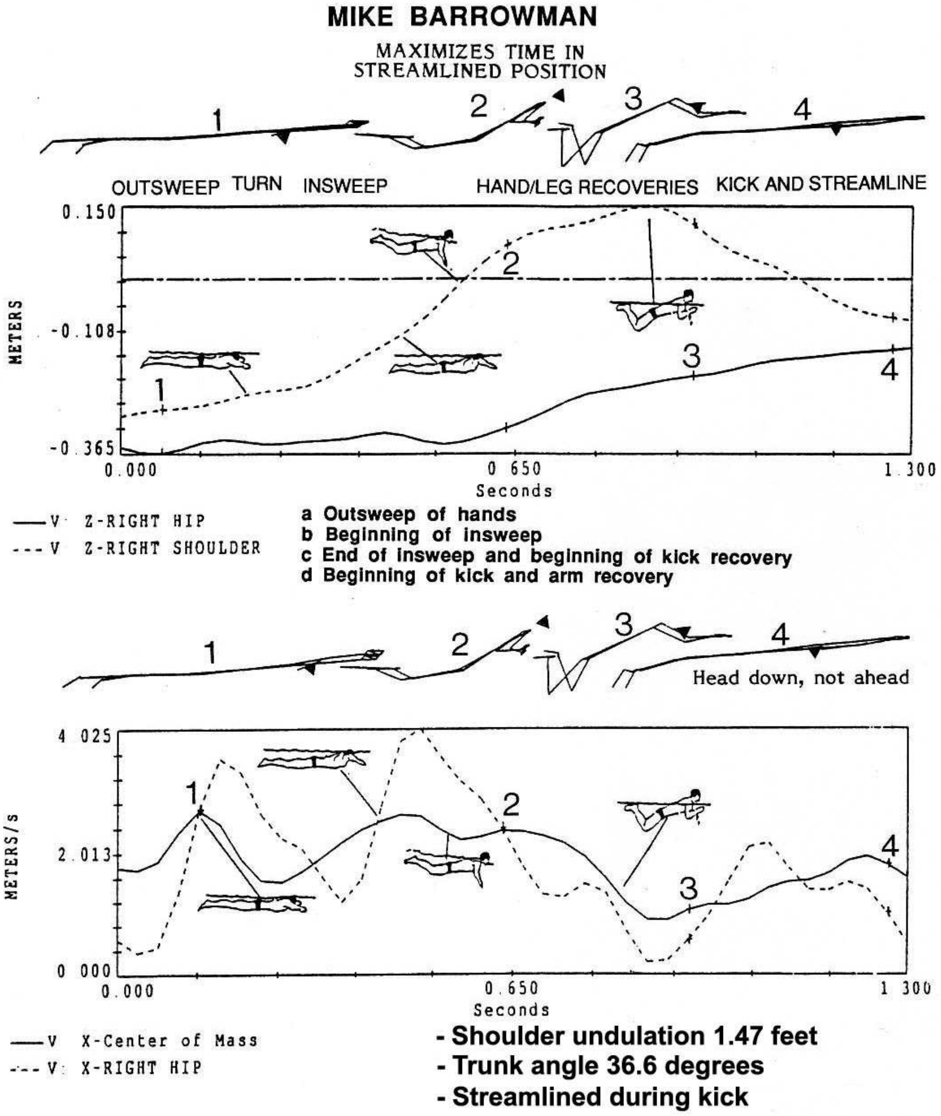


Figure 2. An analysis of Mike Barrowman's Gold Medal swim in the 1992 Olympic Games in Barcelona. The reader's attention is drawn to the acceleration curve graph (METERS/s). The undulating nature of the velocity of the right hip and center of mass is clearly displayed.

When force applications in swimming strokes are not efficient the body will not perform maximally and is likely to deviate from the line of intended progression (e.g., the exaggerated shoulder and head lift in breaststroke; straight arm recoveries in crawl stroke).

Returning to the components of Newton's Second Law, acceleration is required to generate substantial force. Simply, that means the power-phase of arm strokes should accelerate rather than being constant. If that is followed, the largest force acting on the water will be at the end of the power-phase, which stamps that part of the stroke as being the most important (despite it being one of the least emphasized features of arm actions in the sport).

Acceleration requires that the arms provide increasing force. A hand that wobbles or suddenly changes position in a power-phase of any stroke "kills" acceleration for a considerable portion of the effective stroke. Figure 3 represents Alexandre Popov's left arm path of propulsion (Cappaert & Rushall, 1994).

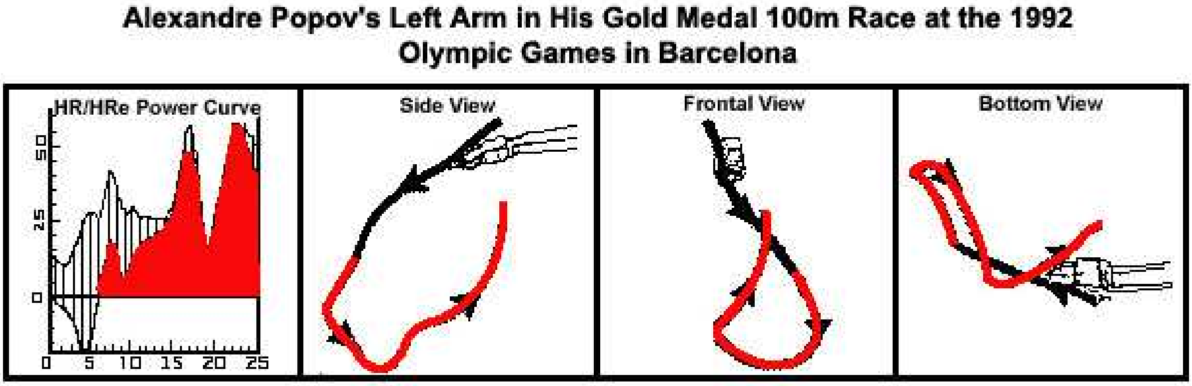


Figure 3. Alexandre Popov's left arm pulling path.

The left window shows the power curve of the pull. It has three peaks. The drop in power after the first small peak coincides with a small change of direction in the early pull (the red portion of the second frame). From there, power is increased until there is a sudden larger drop in power. That coincides with the second "wobble" in Popov's pull. The second frame shows how uneven was the pull that was analyzed. Power drops (reductions in force) occur with seemingly slight movements and are a very important feature to consider when analyzing any stroke. Wobbles that reduce power production are generally termed "instances of slippage".

Secondly, propulsive forces should be in the line of intended progression. Swimmers who swim to the lane lines as they progress are not conforming to desirable force production. Their progression is reacting to the unbalanced forces they are generating.

Thirdly, there is little that swimmers can do to alter the mass factor in the force equation. To maximize that feature the whole arm should be involved in the propulsive phase as opposed to the still commonly emphasized hand. Modern champions use all the arms (the upper arm, forearm, and hand) to create propulsive forces (Rushall, 2009).

Finally, the mass of a swimmer is not particularly important because of the total support of that mass by the water. What is important is that the more resistances and counter-productive forces that are created, the greater is the contradiction against the derivation of maximum benefits from developed propulsive forces.

Newton's Third Law. When a body exerts a force on a second body, the second body exerts an equal and opposite force back on the first.

This law pervades every movement in swimming strokes. If a propulsive force is directed backward, the opposite force is sufficient to propel a swimmer forward. More importantly, is the more complicated phenomenon of a swimmer being supported in water where the central rotation point is the Center of Buoyancy. The Center of Gravity is not that important when suspended in water (see Figure 4). The greater the distance between the Center of Buoyancy and the Center of Gravity, the greater will be the angle of float. For competitive swimming, a swimmer who does not naturally float on the surface in a horizontal plane is lumbered with the need to constantly develop forces that will align the swimmer horizontally as well as attempting to propel oneself forward.

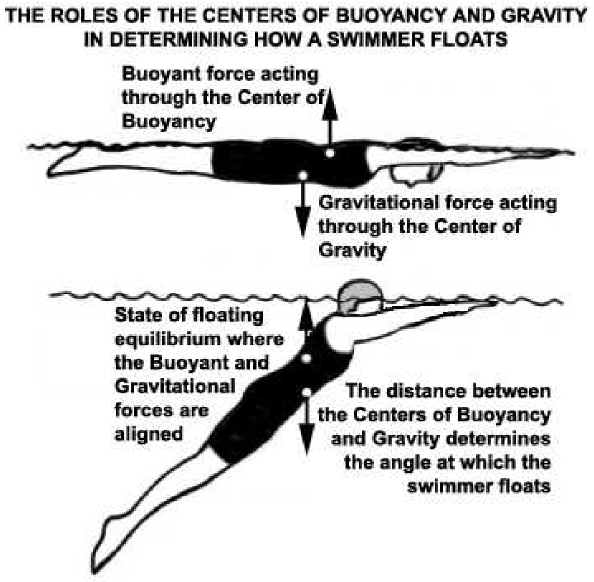


Figure 4. The ideal position for floating is horizontal (the top figure). However, because the centers of buoyancy and mass are not aligned a horizontal position is unnatural. The body rotates until it reaches an angle where the two centers are aligned. That is the natural floating angle.

Of particular importance to swimming coaches is how techniques are corrected. Since swimmers are suspended either side of the Center of Buoyancy, if a technique change is advocated on one side of that flotation point, there is likely to be a reaction movement on the other side. Often that leads to a correction being advocated only to develop another fault as a result of Newton's Third Law. In some cases, two counteracting forces can be developed on the same side of the Center of Buoyancy. For example, if the height of the head-shoulder lift in breaststroke is reduced, the need to angle the arms in their propulsive phase (to develop the force component to cause the lift) should be reduced because not as much vertical force would be needed. Those "on-the-same-side" counterbalancing forces will occur and have little to no effect on the movements on the other side of the Center of Buoyancy.

Figure 5 illustrates how counterbalancing movements can occur on the same side of the Center of Buoyancy. This is typical of what happens in breaststroke and butterfly stroke.

The most obvious and desirable example of this Law is the greater the force developed by the arms in the propulsive phase, the greater will be the swimmer's progression forward.

This very brief explanation of the relevance of Newton's Laws for swimming does not do justice to the importance they have for understanding swimming techniques. Newton's Laws pervade all human movements and cannot be ignored when describing or analyzing competitive swimming techniques. To not consider them is an intellectual gaffe.

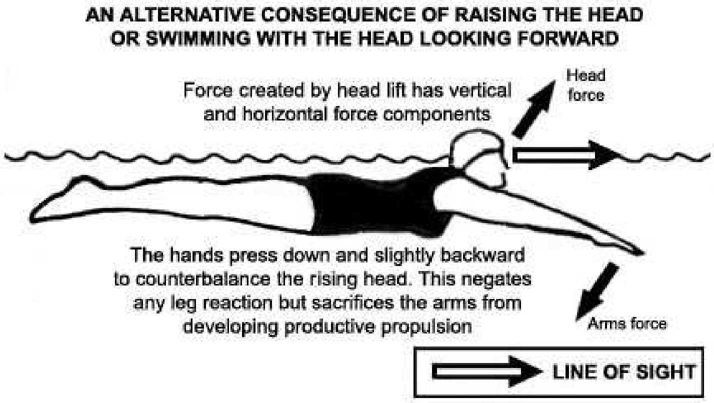


Figure 5. Counterbalancing movements on the same side of the Center of Buoyancy.

Forces that Slow Swimmers

The forces that slow swimmers are termed "resistances". Resistances can be increased when a swimmer does any of three actions: 1) increase the surface of the swimmer in contact with the water; 2) increase the angle of the body and limbs as they travel through the fluid; and 3) collide with and create waves in the water. For each of those actions, there are passive and active components.

Surface Resistance

Figure 6 illustrates three common considerations about surface resistance. The amount of body surface that is in contact with water governs the resistance that exists in a swimmer. The greater the surface area contacting the water at a particular velocity of the fluid in relation to the swimmer, the greater is the resistance. As the progress of a swimmer through water increases, so does the retarding effect of the surface resistance. The relation between the velocity of a swimmer and the amount of resistance through surface resistance is linear. It is in a swimmer's interest to keep surface resistance to a minimum. When the slight roughness of the body/apparel traps a thin film of stationary water on its surface, resistance is minimized because essentially the body is "lubricated" so that water slides on water. There have been some efforts in swimming to manipulate the surface of a swimmer to reduce surface resistance. Usually, they have involved modifying passive resistance.

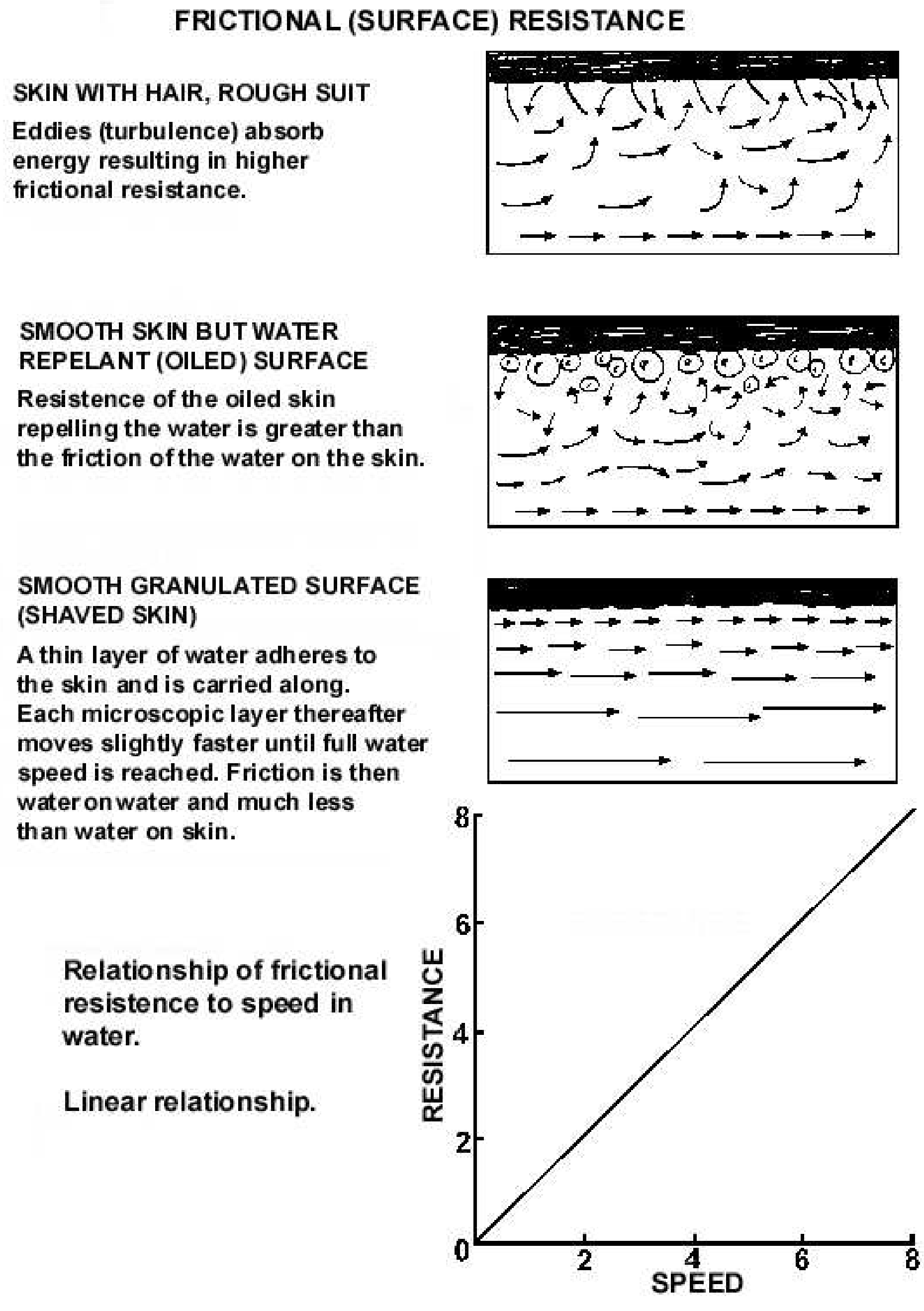


Figure 6. Some common concepts of surface resistance in swimming.

- Shaving was used to reduce surface roughness and therefore, the amount of water dragged along with a swimmer (Sharp & Costill, 1989, 1990). However, many coaches used this phenomenon in error. Most of a swimmer needs to slide through the water with the least resistance possible. However, the propulsive surfaces of the arms should not be slippery, but rather should "grab" the water to the highest possible level. It would then be counterproductive to shave the arms for competitive swimming races. Few coaches take that phenomenon into consideration.

- Swim suits also modified the surface of swimmers as well as the area and profile (Sanders et al., 2001). Once manufacturers "got it right" (Berthelot, 2010; Keul, Bieder, & Wahl, 2010) such suits were banned. The return to a largely skin-exposed swimmer saw performances drop back for a brief period but then to gradually march forward along an expected gradient of improvement.
- At various times lotions and oils have been applied to exposed skin ostensibly to increase a swimmer's slipperiness with water. Usually, the increase in surface tension on the swimmer was a greater force than the friction of water on the skin. In that case no benefit is derived.
- Streamline is the most significant factor affecting passive surface resistance. As water streams over the body, where there are bumps and hollows in a physique, slightly turbulent pools form which negate any appreciable resistance in those areas of the body.

Active surface resistance involves augmenting the surface area of a swimmer. The commonest manifestation of increasing surface resistance is in the execution of a "catch-up" stroking pattern in crawl stroke. When one arm is extended forward without moving in a productive manner, the surface area of the swimmer is increased and consequently, so is surface resistance. The phenomenon of increasing surface resistance gives rise to a technique principle:

If an arm moves slowly or is stationary in a stroking pattern, surface resistance will be increased:

And the corollary is:

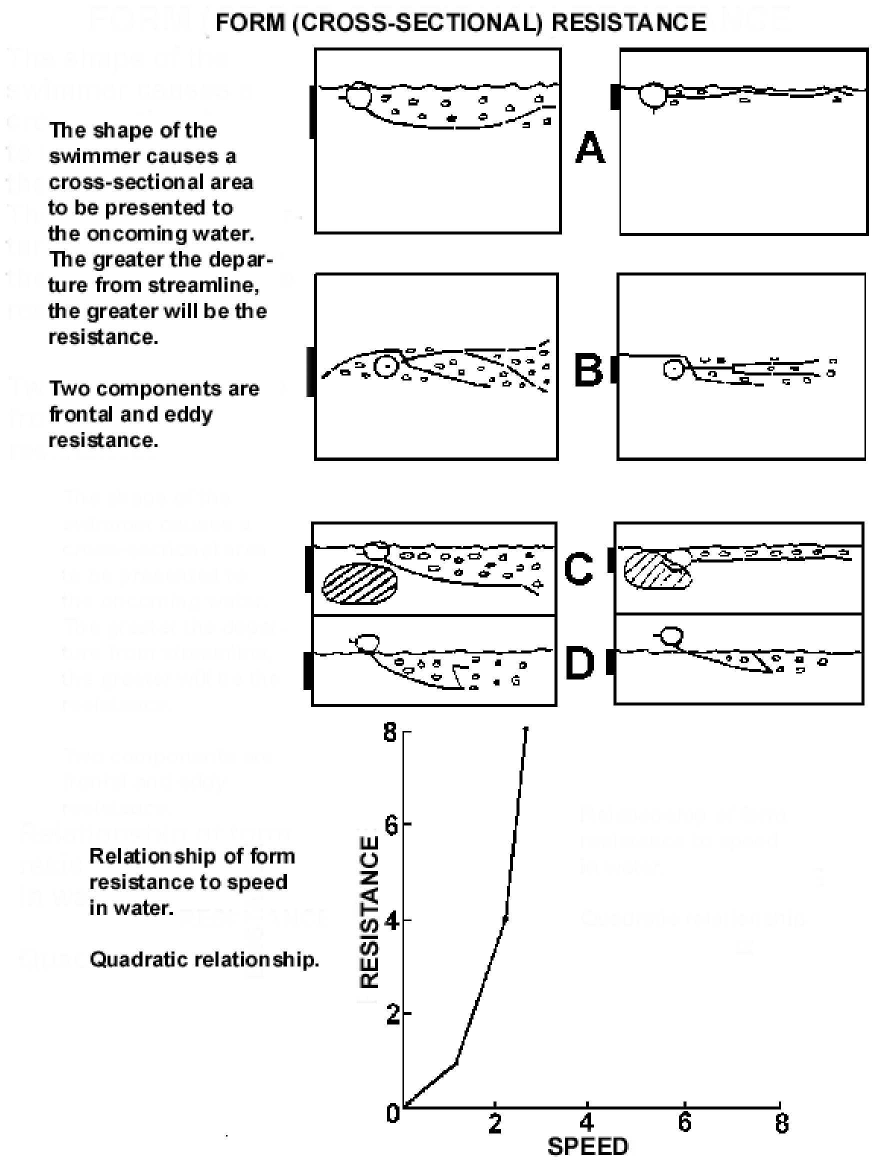
No arm should be stationary or decelerated in the execution of competitive swimming strokes.

Frontal (Form or Cross-sectional) Resistance

The cross sectional area of a swimmer is the widest frontal profile. It usually is not the leading edge or surface feature of the object but the "thickest" visible perspective. In the illustrations of swimmers below in Figure 7, the cross-sectional area is equal to the total frontal view of the swimmers. For example, in the left picture **A**, the cross-section would be what could be seen of the swimmer (the face, chest, shoulders, etc.) from front on, but not the parts that are hidden or in the cross-section's "shadow" (the legs). Although the term "area" is used, it should not be confused with the surface area of the object.

The main reason frontal resistance is very important is that it creates turbulence behind the swimmer. In such pools of eddies, the pressure is less than in the undisturbed water immediately before the swimmer. Consequently, there is a pressure gradient from front to back which is directly opposite the desired direction of propulsion.

The principal action to minimize frontal resistance is to streamline, as illustrated in Figure 7. The cross-section of resistance will never be eliminated but it can be minimized. There are times in strokes, particularly the breathing phases of breaststroke and butterfly stroke when resistance is momentarily increased in a dramatic fashion; that time being during breathing. Figure 8 illustrates a former world-record holder in women's 100 m breaststroke augmenting frontal resistance at various stages in her stroke cycle.


FORM (CROSS-SECTIONAL) RESISTANCE

The shape of the swimmer causes a cross-sectional area to be presented to the oncoming water. The greater the departure from streamline, the greater will be the resistance.

Two components are frontal and eddy resistance.

Relationship of form resistance to speed in water.

Quadratic relationship.

Figure 7. Perspectives of cross-sectional areas of swimmers. The amount of bubbles trailing the figures indicates the amount of resistance incurred

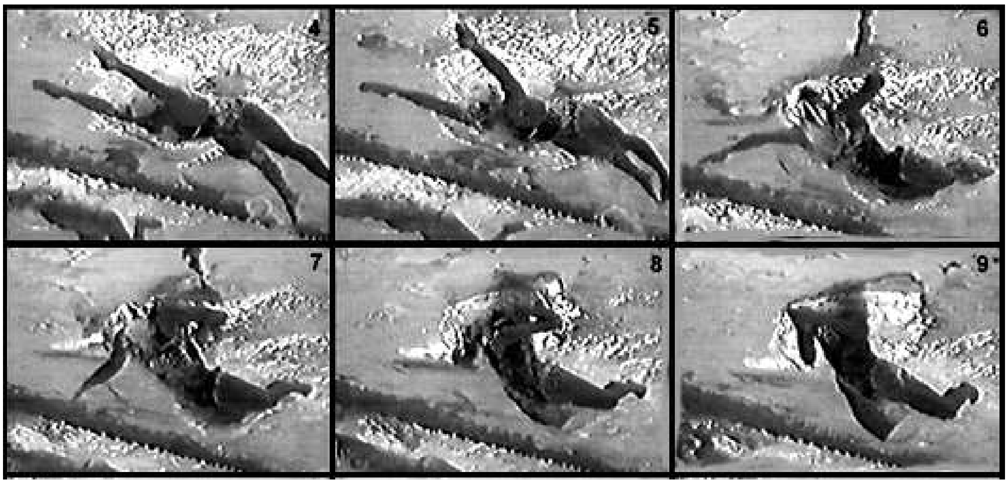


Figure 8. A former world-record holder in the women's 100 m breaststroke augmenting frontal resistance at various stages in her stroke.

Figure 9 illustrates a former Australian champion backstroker augmenting her frontal resistance with hip-sway caused by entering the hands too far behind and across the head. In good backstroke, there should be an absence of any lateral hip movement.

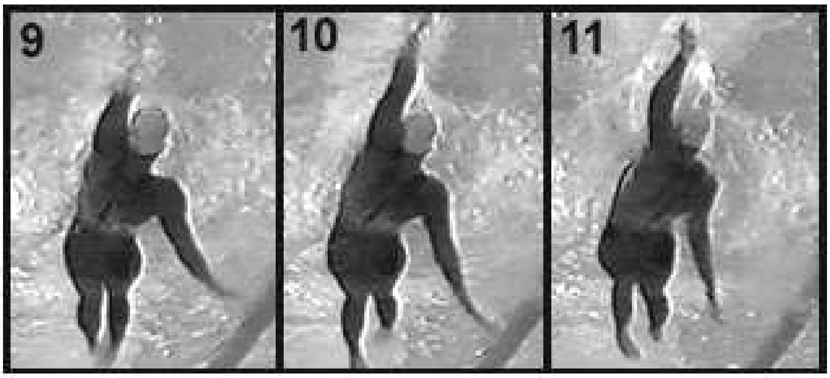


Figure 9. A former Australian backstroke champion increasing frontal resistance by moving her hips laterally, seemingly as a response to entering the hands across and behind her head.

In swimming, lowering the head and shoulders causes the hips to rise making the swimmer flatter. When reaching forward in crawl stroke or backstroke, elevating the shoulder girdle in the horizontal plane produces a "thinner" swimmer. When a swimmer improves streamline, not only is frontal resistance decreased but a second beneficial effect of better fluid flow around the body also occurs. Since a swimmer's head and body do not generate propulsive forces, it is very important to minimize the resistances they create. An ideal streamlined position is one that is sustainable and most economical. A long narrow overall swimmer's position will reduce frontal resistance to a minimum.

"Disruptions to streamline, such as breathing in butterfly and breaststroke, should occur in the shortest time possible and to the least degree possible."

Frontal resistance is more detrimental than surface resistance because the relationship between frontal resistance and velocity is quadratic. There comes a time when so much resistance is created by this resistive force, that no further improvement in swimming velocity is possible no matter how much extra effort is exerted or what training form is undertaken. In that state of "terminal velocity" the sum of the resistances equals the sum of propulsive forces. Any further effort to create force is counterbalanced by a relatively large increase in resistance.

For this form of resistance to be minimized, the following would be a sound coaching principle:

Swimmers should be streamlined for as long as possible at every opportunity in a stroke cycle.

Wave Resistance

When water is moved, waves are formed. Waves have devastating effects on competitive swimmers. There are two forms: 1) external waves that hit the swimmer; and 2) swimmer-generated waves.

External waves in competitive races are caused by other swimmers or the swimmer him/herself. Lateral waves coming from a swimmer (the swimmer's wake) in the next lane can disrupt the progress of a swimmer. However, if the swimmer is positioned so that the wave is slightly behind the Center of Buoyancy, it can be ridden or "surfed" in the manner that is commonly called "drafting".

There is a wave that is pushed forward by a racing swimmer, the "bow wave", and one that follows, the "stern wave". When approaching a wall, the swimmer is hit by his/her own bow wave bouncing off the turn-wall. When turning on timing boards, an attempt to partially kill the bow wave has been made by perforating the board surface. When a turn is executed with substantial speed, the early part of the return lap involves cleaving through the stern wave which is still progressing forward on the previous lap. The effect of the stern wave can be alleviated partially by pushing off the wall and angling downward. The size of both these waves is proportional to the size and velocity of the swimmer.

The bow wave, lateral (wake), and vertical waves are created by the swimmer. They require energy to be formed and so the larger they are, the greater will be amount of energy stolen from the swimmer [that is energy that might have been used for propulsion]. Streamlining and reducing frontal resistance to a minimal amount, will also reduce the size of generated waves.

The vertical wave (or the "downward wave") deserves special mention. In shallow pools, that wave hits the bottom and reflects back upward. If it hits the swimmer (usually in the legs) it will cause further slowing. If a pool is deep enough, the wave will have to travel further than when in a shallow environment. The extended time for that travel means that the wave will still rebound but will miss the swimmer who has progressed beyond the point where it reaches the surface. Depending on the size and velocity of the swimmer, minimum pool depths are required to avoid being slowed by one's own vertical wave. A general rule of thumb for competitive pool depths is for age-group swimmers, two meters, and for championship elite swimmers, three meters.

Bow, lateral, and vertical waves are caused by water being pushed away by a progressing swimmer. When part of the head or body is above the water line, the escape of the water is in only three directions – forward, to the sides, and down. However, if water were able to escape over the top of the swimmer, then there would be four directions in which waves would flow, all being decreased by the addition of the extra escape option. To achieve that, as much as possible, all non-propulsive segments of the swimmer should be submerged. That requires the head and shoulders in all strokes to be pushed down to be level with the hips. Water should flow over the swimmer's head in crawl stroke, on the non-breathing stages of butterfly and breaststrokes, and the face in backstroke. When swimmers are encouraged to "fly over the water" and to "pop up high" when breathing in breaststroke, the three wave directions are increased, resulting in an unnecessary slowing of the swimmer.

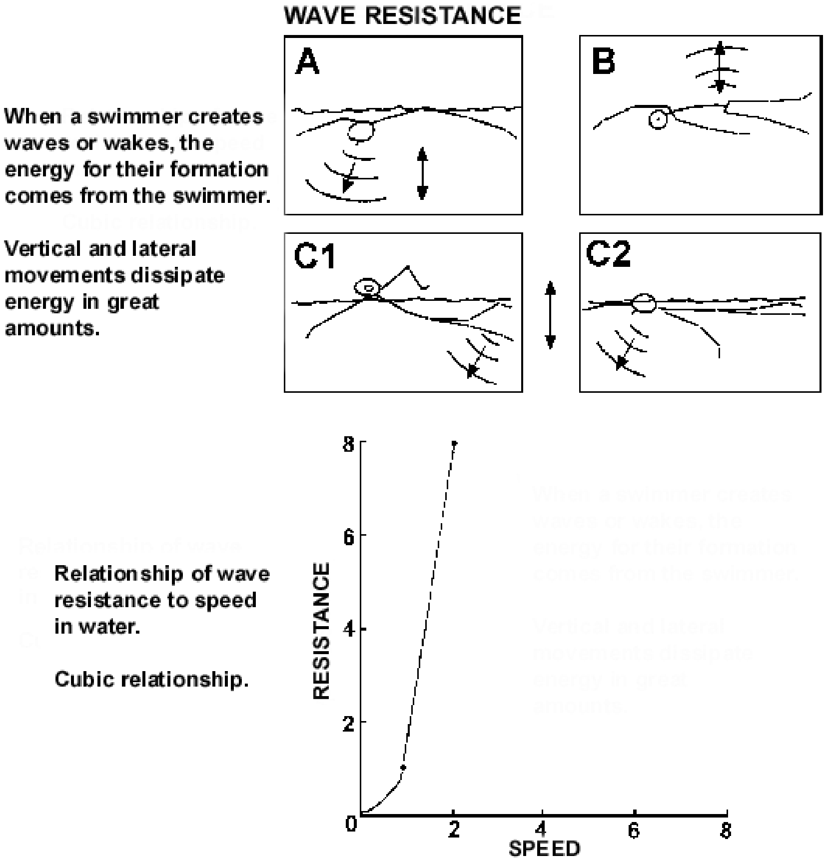


Figure 10. Aspects of wave generation in swimming.

Figure 10 illustrates some technique features that generate unwanted waves. The point being made is that the energy for the wave formations comes from the swimmer. A change in technique to eliminate the erroneous movement segment(s) is the only coaching option. Unfortunately, there are many aspects of competitive swimming strokes that create waves. The dissipation of energy from technique errors has been covered extensively (Rushall, 2012). A major technique error that usually is ignored occurs when a swimmer crashes back into the water after breathing in butterfly stroke and breaststroke. Other actions, such as smashing an entry with straight arms in crawl stroke, kicking very hard irrespective of the demands to counterbalance arm actions, all cause energy to drain from the body to produce movement of water. Such actions are detrimental to a swimmer's progress and ability to sustain a desirable high velocity. Generally, the greater the splash created by a swimmer in any phase of a competitive stroke, the greater will be the energy drain. From this feature there emerge two principles:

The less the lateral wave height (wake) created by a swimmer, the less is the effect of waves;

and

The greater the amount of splash created by a swimmer, the greater is the slowing effect on forward progression.

The relationship between wave resistance ("wave drag") and swimming velocity is cubic. That is an extremely severe negative relationship on progression. It is very likely, that the inability of an elite swimmer to improve in times is caused by wave resistance created by unnecessary action segments. Wave resistance is the most harmful form of resistance in competitive swimming, despite it being the most ignored source of resistance by coaches.

The three forms of resistance briefly discussed above need to be minimized. If they are reduced, swimmers will progress faster and/or for longer periods at a particular velocity. They should be the first priority for coaching technique because they do not require any more training or effort on behalf of swimmers. They are purely teachable features of technique and with their minimization the skill and performances of swimmers will improve.[2]

Altering the Bow Wave in Competitive Swimmers

Heaviness in the lower body parts causes the whole bodily system to angle downward until forces are in equilibrium when the centers of mass and buoyancy coincide. When the head and shoulders are pushed down into the water, the hydrostatic upward pressure tends to cancel out all or some of the previous heaviness. When the head is covered by water as a swimmer progresses at high speed, there is the possibility it could act like a bulbous bow on a large ship. Hypothetically, the similarity is as follows.

The head-down position modifies the way the water flows around the body reducing drag, which increases speed and/or increases a swimmer's efficiency of propulsion. When a considerable part of the head is carried above the water line a bow wave forms in front of it and at a considerable distance when at speed. The size of the wake or lateral waves increases as velocity increases. When the head is down and covered, water flows over the top. The shoulders form a second level of bow wave. If the flow over the head coincides with the wave off the shoulders, the two partially cancel each other and reduce the wake (lateral and vertical wave components). When cancelling-out occurs, the pressure distribution changes along the body thereby reducing wave resistance (Wikipedia, 2013).

Water flowing over a swimmer's head in crawl stroke and backstroke depresses the leading body parts and keeps the swimmer streamlined. When the head is above the water surface, the wake produced is augmented by the wake off the shoulders. A "head-down" position increases the wetted surface of the swimmer which slightly elevates surface resistance. As a swimmer increases in speed, the bow wave increasingly impedes the athlete's progression.

A crawl stroke swimmer with head covered benefits from the cancelling-out effect only at higher speeds. At any speed, the effect on streamline occurs. The visual effects, namely the bow-wave and wake sizes, are altered more obviously at higher swimming speeds. It also is observed that at arm entry in the two alternate strokes, the upper arm disrupts the wake near to and on the side of the head. However, if the wake is viewed for a short time and observed on the side where no arm-entry occurs, changes in wake size can be observed.

Swimming with the head down and head and shoulders at least level with the hips is a position of desirable streamline and a way to reduce wave resistance, particularly the bow wave and its associated wake (lateral waves). This technique adjustment improves a swimmer's propulsive efficiency by reducing resistance.

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[2] A coaching manual exists for altering swimmer techniques: Rushall, B. S. (2013). *A swimming technique macrocycle*. Spring Valley, CA: Sports Science Associates. [http://brentrushall.com/macro/]

Figure 11 illustrates an elite age-group swimmer performing at 200 m race-pace with his head submerged under the water. The bow wave recedes to the shoulders when they are above water level in recovery, the size of the wake off the shoulder is reduced by the flow over the head, and the overall wake height is smaller than when it is developed by the head. These effects are beneficial to competitive swimmers.

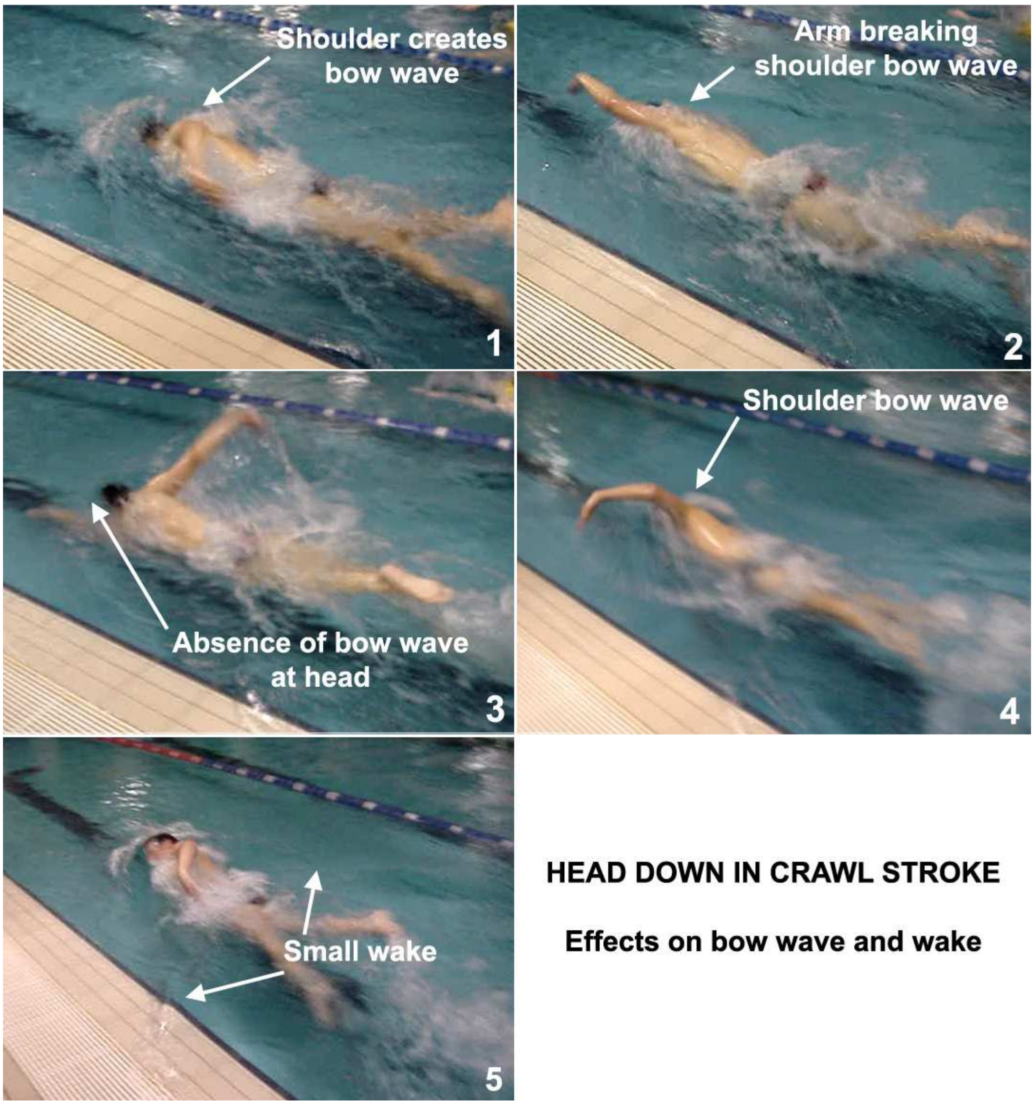

Figure 11. Effects of swimming with a submerged head in crawl stroke swimming.

Cavitation

Cavitation occurs when water pressure is lowered below the water's vapor pressure, forming bubbles of vapor. Cavitation is the formation of vapor cavities in water (small liquid-free zones called "bubbles" or "voids") that are the consequence of forces acting upon the liquid. It usually occurs when a liquid is subjected to rapid changes of pressure that cause the formation of cavities where the pressure is relatively low. That can happen when water is accelerated to high speeds, for example, when a swimmer dives into water or a crawl stroke kick starts from above the surface and slams down into water. Inertial cavitation is the process where voids or bubbles in a liquid rapidly collapse producing a shock wave. Inertial cavitation is usually seen in swimming as obvious splashes from where a swimmer's action has entered/cleaved the water.

When a volume of liquid is subjected to a sufficiently low pressure, it may rupture and form a cavity. Low pressures are behind a kicking leg or following a diver after entry. This phenomenon is "cavitation inception" and forms behind parts of a swimmer that have sufficient amplitude and acceleration. The inception occurs by water being forced outward off an object which greatly lowers the water pressure directly behind the object. Water quickly rushes back into the cavity and is often met with the explosive forces of collapsing fluid vapor bubbles. The meshing of those forces often causes a plume of water to rise noticeably in the air ("splash").

Vapor gases evaporate into the cavity from the water, and so it is a low-pressure area and not a vacuum. Low-pressure cavitation bubbles in a liquid begin to collapse due to the higher pressure of the surrounding water. As the bubbles collapse, the pressure and temperature of the vapor within increases. The bubbles eventually collapse to a minute fraction of their original size, at which point the gas within dissipates into the surrounding liquid via a rather violent mechanism which releases a significant amount of energy as an acoustic shock wave and visible light.

Figure 12 illustrates what happens when a swimmer kicks hard and fast in the belief that it adds to propulsion. No propulsive forces are created, water is disturbed to a great deal being a mix of cavitation and turbulence formation, and a great amount of energy is expended in this fruitless action.

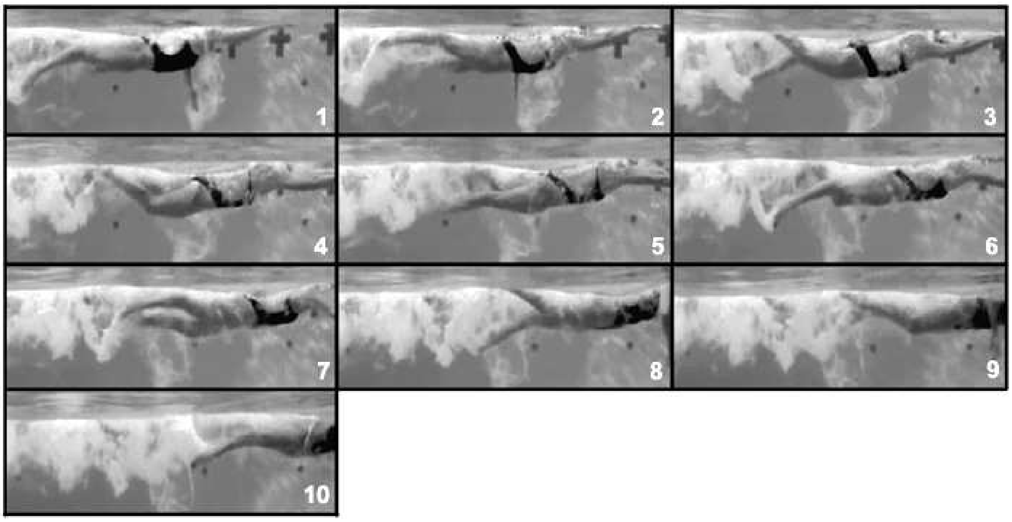

Figure 12. Kick-dominated crawl stroke in a female 2012 USA Olympic Games Trials qualifier.

Cavitation should be of concern to swimming coaches because it can occur within the power-phase of arm strokes. Very strong men, such as body-builders, often are able to pull their arms through water with significant speed and acceleration. However, although they may be very strong, that strength is sufficient to move water and cause cavitation rather than "fixate" in the water and propel them past the inappropriately labeled "anchored arm". It is possible to be too strong when attempting to apply force in a fluid. That should seem odd because many coaches attempt to build the greatest strength possible in their swimmers despite strength not being a determinant of success in female swimmers and to only a minor extent in male swimmers

(Sokolovas, 2000). Since water is relatively "fragile" when compared to other sporting environments, the better strategy to improve performance is to develop greater areas of propulsive surfaces. As swimmers have continued to achieve higher velocities swimming on the water surface, there has been a change in what is occurring with arm strokes, the arms being the main sources of propulsion in surface swimming. Over the years, concentration on the hands as the propelling surface was initially advocated (Counsilman, 1968, 1970); then the propulsive surface was expanded to be the forearm plus the hand (Cappaert in Troup, 1992); and finally has reached the stage where the three segments of the arm constitute the ideal propulsive surface (Rushall, 2009). Increased propulsion does not come from having the greatest strength possible but from applying forces with the greatest propelling surface possible so that cavitation does not occur.

The greater the water depth at which the fluid acceleration occurs, the less the tendency for cavitation because of the greater difference between local pressure and vapor pressure. Thus, it would be easier for a swimmer to cause cavitation on the surface than at a depth of possibly two meters (Marinho, Barbosa, Mantripragada, et al., 2010; see below). After a brief period, once the cavitation flow slows down again, the water vapor will generally be reabsorbed into the water.

Cavitation occurs frequently and easily in surf swimming. Behind a broken shore wave, the water is usually roiled and turbulent ("white water"), conditions that support a lower fluid pressure than in stationary water. When a swimmer attempts to propel him/herself in that type of water, the arms slip through the water very quickly while forward progression is very slow and in some circumstances stationary as the water moves past the swimmer. The ease with which vapor pressure is reached in "white water" in the surf is because of the low gradient between the water and vapor pressures. The only ploy to avoid such unproductive swimming is to remain deep in the surf and swim underwater until the water is less disturbed and "greener".

The depth at which double-leg kicking is performed is important. Marinho, Barbosa, Mantripragada, et al. (2010) used a model to control depth and measure drag coefficients and forces at various depths. Table 1 contains their results. The implication of their study was that the deeper a swimmer performs double-leg kicking the likelihood of improved performance is increased. The most likely depth in races is between 1.50 and 2.00 m, with post-dive kicking being easier to perform at the greater depth. The slowing effect of the water is reduced by ~40-45% at those depths. When a swimmer is capable of performing substantial (more than 10 kicks) kicking after a turn, it might be advantageous to push off the wall at an angle that will take the swimmer to a deeper orientation than if the off-the-wall push was horizontal.

Cavitation and its associated splashes should be avoided in swimming strokes. If effort is involved in generating cavitation it is wasted energy and detracts from performance efficiency.

TABLE 1. DRAG COEFFICIENTS AND DRAG FORCES AT VARIOUS DEPTHS FOR A HUMAN MODEL (Marinho, Barbosa, Mantripragada, et al., 2010).

Depth	**0.20 m**	**0.50 m**	**1.00 m**	**1.50 m**	**2.00 m**	**2.50 m**	**2.80 m**
Drag Coefficient	0.67	0.62	0.53	0.44	0.36	0.30	0.28
Drag Force (N)	100.20	92.30	80.50	65.40	53.40	44.70	42.00

Performing Exaggerated or Unneeded Actions[3]

To achieve a high level of swimming efficiency, swimmers need to perform only necessary movements at the least possible magnitude. Exaggerated actions consume energy beyond that which is actually required for efficient progress.

Breaststroke breathing is a common exaggerated movement. The higher the mouth is from the water surface, the greater is the energy demand to lift the head, neck, and shoulders. As well, the higher the movement the longer it takes to complete the action. That results in excessive energy demands over an extended period. However, there are two other obvious negative aspects to high-breathing movements in breaststroke.

- When a large portion of a swimmer is raised above the water surface, there is a large loss of energy as the swimmer collapses back down into the water displacing a large amount of fluid, the energy for its displacement coming from the swimmer. The provision of energy to move water unnecessarily reduces the capacity of the swimmer to energize actual progression in a race.
- When inhalation occurs close to the surface, the bow wave is small. The best inhalation would be a thrust of the jaw forward through the bow wave. That action presents a narrow frontal area keeping the bow wave small. However, the higher the head and shoulder lift, the greater is the bow wave because the frontal area is increased. As the lift goes higher, the height of the bow wave increases requiring the swimmer to lift even higher. The outcome of the exaggeration is that at the time of inhalation, the bow wave is created by the frontal area of both shoulders and the chest. That is a relatively huge resistance and is clearly seen when a large splash off the top of the wave is propelled upward and forward. For a brief period, forward progression likely ceases causing an excessive need for extra energy when forward progression recommences. The splash created by the breathing action is an indication that the breathing action is excessive.

Butterfly recovery is another action that commonly is exaggerated. The recovering arms only need to travel over the water. Excessive clearance is not required. As with any movement in water, the higher an action occurs out of the water, the greater is the reactive downward force (Newton's Third Law) and the greater is the amount of water moved (and the greater is the loss of energy to produce that movement). Not only is a high recovery energy-demanding, it also creates reactions in the swimmer's body (a deeper travel of the shoulders), legs (a larger kick is required to counterbalance the higher recovery start and finish), and hips (the body's undulation of the hips and shoulders increases in a detrimental manner). Undulations also move water (energy-sapping) and are not of any movement form that produces propulsion as it does in other aquatic animals.

The above are examples of the detrimental effects of exaggerated actions. There are also unneeded actions that consume energy, create resistance, and deplete a swimmer's energy reserve. The most common examples are exaggerated actions but pure actions that have no capacity for generating forces that create progression are also common.

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[3] The factors discussed here are presented in greater depth in Rushall (2013).

The breaststroke recovery that breaks the surface as the arms are thrust forward is an unneeded action. The harmful effects of the action are heightened when the arm thrust forward is also emphasized arbitrarily.

- When the arms are raised up and then "banged" back into the water unnecessary drains on energy reserves occur to create the vertical forces to achieve the lift and to move water upon return. The most expedient action is to recover the arms underwater and directly forward with minimal frontal resistance. Some coaches point to dolphins/porpoises leaping out of the water as a sound reason to do this form of recovery. That is wrong. Aquatic mammals need to break the surface to breathe, but the rest of the time they remain totally immersed. When forced to breathe, they need to be above the surface as long as is needed to inhale and as high as needed to avoid inhaling fluid. There is no commonality between the breaststroke arm-recovery and aquatic mammals' breathing. That is a false analogy and false reasoning.
- With the same erroneous breaststroke recovery, there often is an attempt to thrust the arms forward as fast as possible. That has harmful effects on a swimmer's progression. In the thrusting action, there is an equal and opposite force created that is contrary to the desired direction of progression (Newton's Third Law). If the arms were stopped suddenly and completely, there would be a transfer of momentum from the arms to the swimmer, which is a brief benefit. However, if the hands split when nearing the end of the thrust that minor theoretical benefit would be lost. This spectacular but harmful form of recovery is clearly a technique error created by an unnecessary action.

A very common technique error that is caused by both exaggeration and needlessness occurs with kicking actions. Many coaches believe kicking to be propulsive, which other than for breaststroke they are not (Brooks, Lance, & Sawhill, 2000; Deschodt, 1999; Rushall, 1999, 2013). Big kicks create an excessive drain on a swimmer's reserve of energy and create excessive turbulence and resistance, which decrease the performance potential of a swimmer.

In crawl stroke, an unneeded/inadvisable action occurs with the "catch-up" or "overtaking" cyclic arm pattern (Fernandes et al., 2010; Millet et al., 2002; Schnitzle et al., 2008). The outstanding fault of this action is that it develops a period where there is no propulsive force. That constitutes an inertial lag, where the only forces acting on the swimmer are resistances that slow forward progression. The change from exaggerated slowing to exaggerated propulsion is an extremely costly transition in terms of energy consumption. The drain on energy is somewhat akin to driving an automobile by slowing down and speeding up repeatedly (gas mileage drops markedly). The catch-up stroke violates a desirable example of Newton's First Law.

The examples cited above could be avoided if known principles of fluid mechanics and physics were applied. Not knowing what does and does not help swimmers to perform produces less than desirable swimming techniques, which do not result in the fastest or most efficient swimming.

To move toward the end of this presentation a final criticism of coaching concerns the relationship of technique and energy provision. The technique required to progress at a particular velocity is dependent upon a unique provision of energy. As velocities change, so do the nature and amount of energy demands (Rushall, 2011). There is a belief that technique is best taught at slow aerobic speeds the fallacy of which has been exposed (Rushall, no date). The outcome of current knowledge in motor learning and neurophysiology is that racing techniques are best taught at racing speeds. If that is followed, the energizing of the techniques to be used in races will be specific and appropriate. Consequently, "technique work" practiced through slow swimming, the use of drills, and with the employment of devices are all erroneous practices. They contravene what is known in science.

This has not been a complete coverage of the physics and movement factors involved in competitive swimming. Swimming is so unnatural for humans because the multi-jointed structure with no obvious aquatic adaptations leads to very complex actions. A full analysis of each joint's function would be a very challenging academic task. However, taking care of the more obvious features is a step in the right direction particularly if it results in relevant and minimizes or eradicates irrelevant actions.

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