exists, as we have seen, when a cylinder or sphere rotates in a flow and so introduces circulation into a uniform stream. The Magnus effect also explains the flight of a cut tennis ball or the swerving flight of a golf ball.

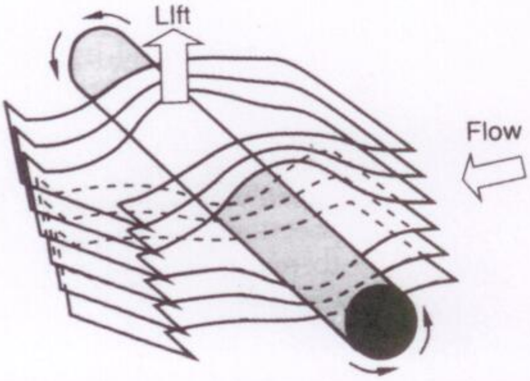


Figure 4.5 Lift generated by a rotating cylinder in horizontally moving flow.

Flow Circulation and the Human Swimmer

Although human limbs cannot develop lift propulsion in exactly the same manner as a revolving cylinder, this basic example of the Magnus effect shows that lift depends on the presence of a bound vortex around a propelling member that is superimposed on a flow.

Later in this chapter, I'll show how human swimmers often generate lift during certain phases of the swimming stroke by using this mechanism. The necessary flow circulation is developed mainly by directional changes of the foil-shaped hand aided by a significant degree of hand-forearm rotation particularly in the arm actions of the butterfly and breastroke. However, we first need to enlarge on the subject of circulation with specific reference to the profile of the propelling member.

Lanchester's Theory of Circulation

In the case of an airfoil, there is no source of mechanical rotation so it is not obvious at first sight how it develops lift by creating circulation. F.W. Lanchester (1907), with what proved to be amazing insight, took the bold step of assuming that an airfoil's lift is associated with circulation even though the airfoil does not rotate.

This assumption must have seemed very dubious at the time, but we now know that any kind of body must have circulation around it to develop lift in a flowstream. Unless the body is specially shaped, however, the circulation is very feeble, and there is no lift. As I mentioned earlier, an airfoil has a specially designed shape that when the airfoil is propelled through a fluid, generates a strong circulation without causing a large drag. It is just this property that enables propulsion without rotating surfaces to create lift.

How an Airfoil Creates Circulation

We can now study airfoils as specially designed devices that do not need to rotate but are still able to create and maintain circulation. If we could move with an undisturbed flowstream and watch the fluid moving over an airfoil, the fluid would seem to circulate. The fluid moving upward and over the top of the airfoil flows more quickly then the main flowstream, whereas the fluid underneath flows more slowly; relatively speaking, the flow appears to move in a circle.

The idea of relative flow around an airfoil is a different perception of circulation. In this case, the bound vortex is a mathematical concept represented by the surface of the airfoil itself and not actually visible. The bound vortex around an airfoil is usually denoted as shown in figure 4.6.

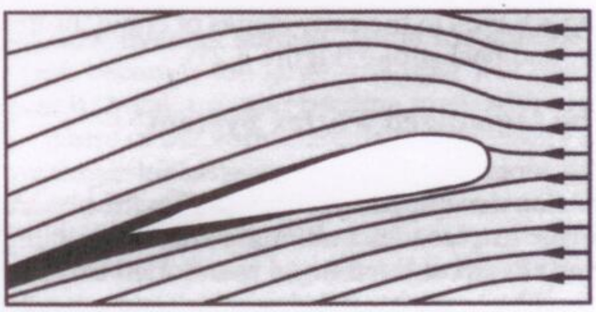


Figure 4.6 A bound vortex around an airfoil is a mathematical concept represented by the profile of the airfoil itself and is not actually visible.

How a Starting Vortex Creates Circulation in the Form of a Bound Vortex

To see what happens when a foil starts to move through a stationary fluid, hold a piece of inclined cardboard in smoke and move it from rest. You'll see an eddy shed from its trailing edge (figure 4.7). This is called a *starting vortex*, which is generated every time a foil starts its movement. A starting vortex is also generated when the hand or foot of a skilled swimmer starts a propulsive impulse in a particular direction.

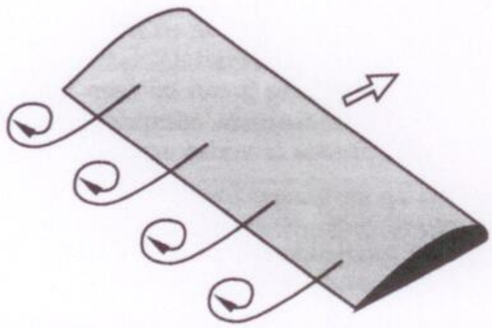


Figure 4.7 Eddies shed from the trailing edge of a moving foil.

One of the rules of fluid dynamics is that a vortex cannot be created without the production of a countervortex of equal strength circulating in the opposite direction (the principle of conservation of angular momentum). In the case of an airfoil, the countervortex is in fact the bound vortex, responsible for circulation and the production of lift, and it owes its continuing existence to the shearing forces over the surfaces of the foil (figure 4.8).

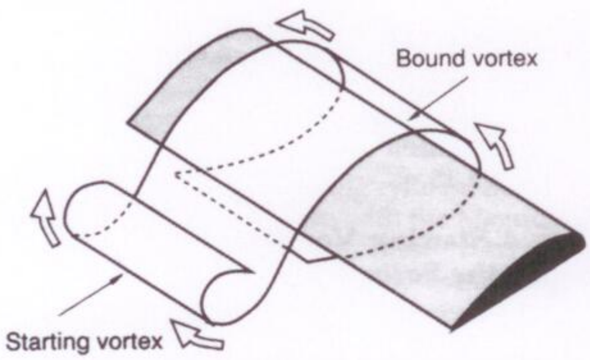


Figure 4.8 Starting vortex and the production of its countervortex, the bound vortex.

Experiments with a revolving cylinder in a flow channel show the reappearance of the starting vortex once the flow is switched off and circulation has ceased. Right at the end, the starting vortex appears, almost like a movie played in reverse. In the strict technical sense, however, this vortex is known as the finishing, or shed, vortex.

It is provable mathematically that because a flow does not contain a circulation at the start of a movement through it, it cannot contain a circulation at the end of the movement. This same principle applies to lift propulsion in human swimming. The shed vortex at the end of each propulsive impulse within a swimming stroke indicates that the propulsive effort in that particular direction has ended.

From the preceding it can be seen that any lift-producing mechanism comprises the following three phases of vortex action:

1. The starting vortex
2. The bound vortex
3. The finishing vortex (also termed the shed, or free, vortex)

Tip, or Trailing, Vortex

As well as providing lift, the difference in pressure between the lower and upper surfaces of a foil causes a related effect known as tip vortex, or trailing vortex. Explained simply, tip vortex results from the tendency of any fluid to flow from high to low pressure. As there is no barrier at the foil tips separating the high from the low pressure areas, the fluid leaks from underneath the foil to the top surface (figure 4.9). This flow, or leakage, deflects the fluid on the top surface slightly inward and that on the bottom surface outward, introducing a third dimension to the flow around the foil (figure 4.10).

The streams meeting at the foil's trailing edges cross one another to form a series of small trailing vortices that join into one large vortex at each foil tip. The energy used in the formation of the vortex trail appears as the induced drag. Obviously, to increase speed, extra thrust is needed to overcome the resistance caused by induced drag (figure 4.11). Even on a foil of finite span in steady motion, however, induced drag cannot be eliminated, for it is a necessary adjunct of lift. Similarly, a swimmer propelling with lift force predominating always produces induced drag. Accidental flow aeration (entrapment of air in the water) often produces visible evidence of trailing vortices on a swimmer's hands in the early stages of crawl, butterfly, and backstroke (figure 4.12). In these instances we know that lift is the predominant force acting on the swimmer's hand at the start of the stroke. However, if a swimmer's hand enters the water and immediately pulls directly backward, a predominant drag force is created, and instead of tip vortices, a typical loop (elongated) vortex is shed from the hand early in the stroke.

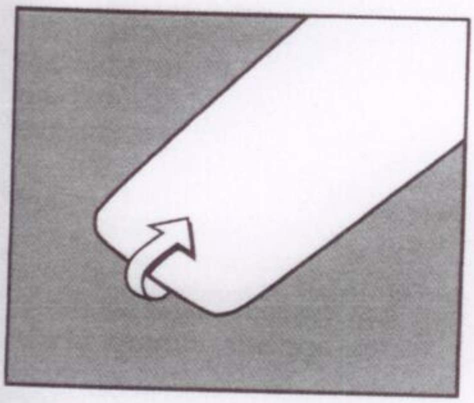
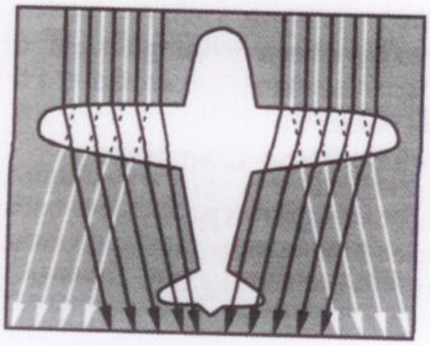


Figure 4.9 As there is no barrier at the foil tips, the fluid leaks from the high-pressure area beneath the foil to the low-pressure area on the top surface.



Low-pressure air = black

High-pressure air = white

Figure 4.10 Foil tip leakage introduces a third dimension to the flow around the foil.

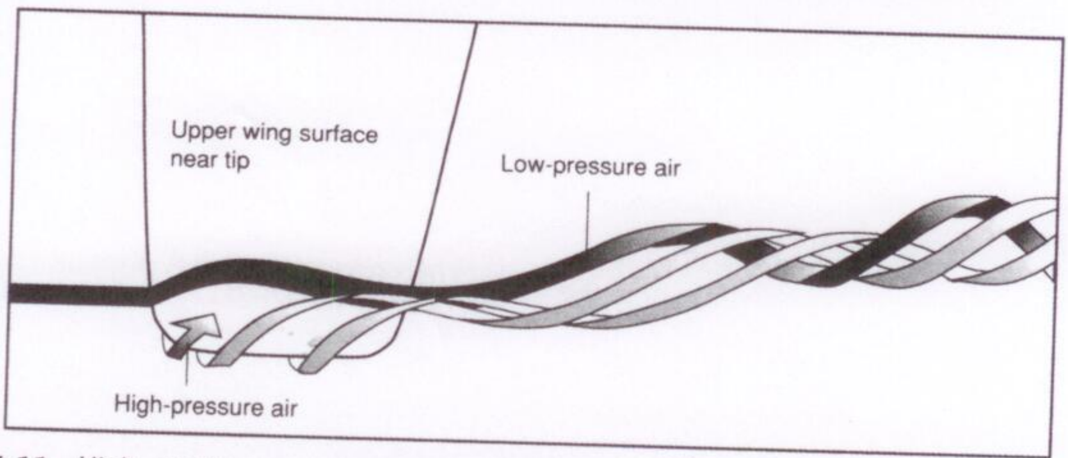


Figure 4.11 High- and low-pressure streams meet to form a vortex trail.

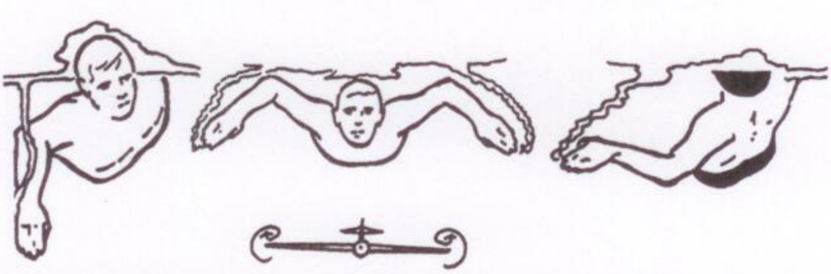


Figure 4.12 Trailing (tip) vortices are often shed from a swimmer's hands in the early stages of the crawl, butterfly, and backstroke pull.

The Organized Vortex System

The term *organized vortex system* refers to propulsion developed by foil-type lift with a bound vortex in place and trailing vortices springing from the tip of the foil. As mentioned earlier, a propeller is a rotating foil or wing. When lift is uniformly distributed along its blade span, an organized vortex system exists. Similarly, when swimmers use the hand like an airfoil, an organized vortex system will exist.

Foil-Type Propulsion in Steady Flow Conditions

The use of foil-type lift propulsion, in the strictest sense of the term, is limited to steady flow conditions in which the flow pattern does not change over time. Such is the case for a conventional airfoil lift-producing mechanism. This means that the foil must be positioned at an angle of attack that results in a steady circulating flow over its surface.

If the foil's angle of attack becomes too large, the flow detaches from it, breaks up, and becomes unsteady, causing a loss of the vortex circulation necessary for creating lift. This phenomenon is called *stall.*

Airfoils are designed to create the steady flow circulation that causes constant lift propulsion. Lift may be generated in any direction. A swimmer's arm can be used as a swimming foil, if angled properly (figure 4.13); for example, as a crawl swimmer's arm enters the water with the elbow set higher than the wrist, its cambered upper surface causes the oncoming flow to move more quickly over the upper surface of the arm and more slowly along the lower surface. The different flow velocities over the upper and lower arm produce the pressure differential necessary for lift. In this case, the lift is upward, causing a high position of the upper body in the water but not contributing directly to propulsion.

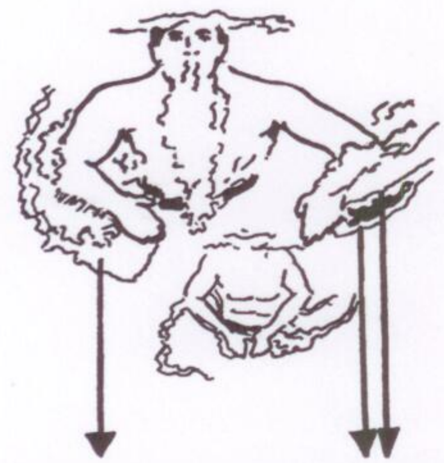
Figure 4.13 Different flow velocities over the upper and lower arm produce a pressure differential.

As the hand moves further into the stroke it assumes an angle favorable to producing forward-inclined lift. This position lasts only a short while, however. Most skilled swimmers establish steady flow propulsion (with an organized vortex system) at the beginning of the stroke. But subsequent directional changes of hand and limb cause increased angles of attack that quickly lead to quasisteady, then nonsteady, flow. In crawl, butterfly, and backstroke, it soon becomes difficult to continue developing lift circulation by means of the conventional airfoil lift-producing mechanism because the changing postures of the hand cause too large an angle of attack.

The hand and forearm action in swimming propulsion has been likened to that of a propeller blade. But the 360-degree rotation around an axis of a mechanical propeller is anatomically impossible for a hand. An airfoil can maintain an angle of attack that produces continuous steady flow circulation. But photographs taken in a wind tunnel show what happens to the flow reaction around a cranked plate (a type of foil) as the angle of attack is changed. The flow changes from steady to quasisteady and then to unsteady. Under unsteady flow conditions, ideal foil-type lift becomes impossible.

The onset of unsteady flow conditions is marked by the tendency of the vortex trail to swell and start to burst. If the foil's angle of attack continues to increase, the vortex trail detaches from the foil, indicating that circulation has been lost and that an organized vortex system is no longer in place. Foil-type propulsion, in its accepted sense, has terminated. Similarly, when a swimmer's hand approaches too large an angle of attack, conventional foil-type propulsion is no longer possible.

The illustrations of an Olympic butterfly champion show reactions similar to those around a cranked plate in the wind tunnel (figure 4.14). This is not a unique observation, for the flow reactions produced by skilled swimmers consistently indicate that human swimming propulsion takes place in conditions of unsteady flow.



Right hand is pitched at too large an angle of attack, causing trailing vortex to swell and start to burst. Trailing vortex is about to detach from hand, indicating foil-type lift is ending (see inset figure).

Left hand is pitched at ideal angle of attack. Thin trailing vortices are characteristic of steady flow. Vortex sheet is seen as dark area between trailing vortices.

Figure 4.14 Butterfly stroke, quasisteady flow (right hand) and steady flow (left hand). Adapted from photos courtesy of James E. Counsilman.

Propulsion in Nonsteady Flow

The essential problem, hitherto ignored in analytical studies of human swimming, is that swimming propulsion occurs mainly in unsteady flow. There can be no doubt about this; the stroke mechanics of even the most skilled swimmers consistently produce unsteady flow reactions because a swimmer's hand, as it travels through a wide range of movement, quickly assumes too large an angle of attack for steady flow to continue. Although an airfoil, which is specifically designed for the purpose, can maintain the ideal angle of attack to produce the steady flow necessary for constant lift propulsion, a swimmer cannot use the hand like a conventional foil throughout a swimming stroke. The action of the hand in the swimming strokes simply cannot be compared with steady state aerodynamics.

Another important reason why the hand does not operate as a conventional airfoil is that at the start of an airfoil's movement (for example, an airplane at takeoff), the net lift around the airfoil is very small. The smooth characteristics and lift of steady flow are established only after the airfoil has moved about ten chords (a chord is the width of the foil from leading edge to trailing edge) from its starting point. The interaction between opposing currents of air (or fluid) that delays the creation of steady lift is called the Wagner effect and contributes an unavoidable nonsteady phase in the action of normal airfoils. A swimmer's hand is not in the water at an ideal angle of attack long enough to obtain constant lift in the manner of an airfoil.

The question, then, is whether lift-force propulsion can be developed in unsteady flow conditions. It can, but the lift-producing mechanism is an unconventional one that does not require the propelling member to be placed at an ideal angle of attack.

The lift force generated by a foil is directly proportional to the foil's surface area and the density of the fluid in which it is moving. Given that the density of water is 800 times the density of air, the human hand moving in water generates a force equal to that generated by a surface 800 times its size moving in air at the same speed. Because the lift force generated by a foil is directly proportional to the square of its speed through the fluid, a 40 percent increase in the speed of the hand when employed as a foil can almost double the propulsive force generated.

In swimming, lift-force propulsion is developed in unsteady flow primarily by the directional changes of the foil-shaped hand as it moves through the stroke. The gradual rotation of the hand and forearm as a unit as the stroke progresses is an important part of this lift-producing mechanism. In all the styles of swimming, the stroke commences with the palm facing outward (to lesser or greater degrees, depending on the flexibility of the individual swimmer). As the arm reaches midstroke, the elbow reaches maximum flexion at plus or minus 90 degrees, thus indicating a considerable amount of hand-forearm rotation since the stroke commenced.

As stated, it is the rotating hand-forearm unit, moving laterally or transversely across the line of the body's forward movement, that generates lift. This action causes a pressure differential in the flow, which in turn sets up the flow circulation around the hand and forearm necessary for lift to occur. As the arm bends and the hand and forearm gradually rotate, the flow is swirled or wrapped around the hand and forearm. This swirling flow constitutes the bound vortex, or circulation, whose superimposition on the general flow is necessary for lift. As the arm extends again and the final propelling thrust of the stroke is applied, this circulating flow is gradually unswirled or unwrapped from the arm in the form of a shed vortex.

As already explained, directional changes of the hand combine with a significant range of hand-forearm rotation to set up the mechanism necessary for creating flow circulation. These flows are readily visible in shadowgram tests conducted at low speeds, when the flow is not too compressed to be easily seen.

You may conduct similar tests by simply moving a spoon or any other suitable foil-shaped object through the appropriate directions in a container of water. If you have a strong overhead light and the bottom of the tank is white, you'll see the shadow cast by the resulting vortex on the bottom of the tank and be able to note the different flow reactions produced by rectilinear and curvilinear movements. This simple test shows distinct differences between the flow reactions set up by drag propulsion (pulling directly backward), the conventional airfoil mechanism, and a curvilinear pulling pattern (figures 4.15a, 4.15b, and 4.15c).

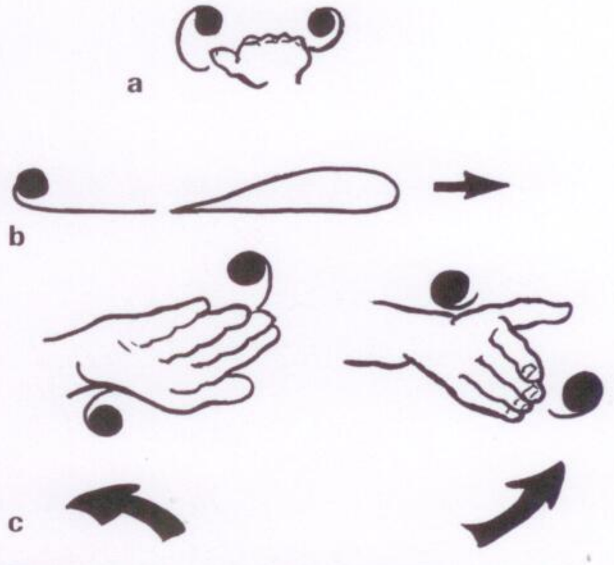


Figure 4.15 Typical flow reactions: *(a)* drag propulsion (pulling directly backward); *(b)* conventional airfoil method; and *(c)* outward and inward sculling (curvilinear pulling patterns, especially in butterfly and breaststroke). In the inward and outward scull, there are always leading edge and trailing edge vortices around the hand.

Vortex Reactions in Producing Lift

Essentially, fluid dynamics as applied to lift-force propulsion in swimming comprises a three-fold sequence of events:

1. At the start of a propulsive impulse, a starting vortex produces a bound vortex around a hand, foot, or limb.
2. The bound vortex is then manipulated in such a way as to enable lift force to be applied.
3. When circulation (in the form of a bound vortex) can no longer be produced and maintained, a vortex is shed, indicating that the propulsive impulse has ended.

The Significance of the Shed Vortex

A vortex is shed whenever a propulsive impulse ends. The analysis of these vortex patterns produced by each swimming stroke provides a new perspective from which to view swimming efficiency. The pattern of shed vortices a swimmer leaves in the water provides an instant history of the swimming stroke, because each propulsive impulse within the overall stroke produces a distinctive type of vortex as its signature.

Recognizable patterns reveal how individual swimmers apply their power. By its size, shape, direction, velocity, and placement in the flow field in relation to the swimming stroke, the shed vortex reveals the type of propulsive mechanism the swimmer has used and the net effectiveness of the propulsive impulse just completed.

Kinetic Energy

A shed vortex represents a form of kinetic energy, or in other words, the energy of motion. We know that energy cannot be created or destroyed, but it can be transferred from one type to another. Energy is transferred from the swimmer to the water in the form of kinetic energy whenever a vortex is shed. (In fact, energy is being changed from one form into another whenever work is done or energy expended.) Vortices shed at random and not at the end of a propulsive impulse indicate wasted energy that a swimmer is not applying to the water in the most effective manner.

Studying Flow Reactions to the Swimming Stroke

I conducted a study that sought to identify flow reactions common to the stroke mechanics of world-class swimmers. A methodical analysis of underwater movies, slides, and photographs consistently revealed similar patterns of vorticity (Colwin 1984a).

By correlating commonly observed flow reactions with established fluid dynamic principles—particularly those concerning lift propulsion—I attempted to establish a basis for further study. The flow visibility was not always complete because observation depended largely on accidental air entrapment (aeration) in the swimming stroke; nevertheless, it was possible to form a synthesis of the flow reactions that could be anticipated during key phases of propulsion. More recently, I have noted the advantages of underwater video recordings of swimmers during actual competition. When swimming at speed, most swimmers accidentally entrap enough air into the water to make the flow reactions almost continuously visible.

I systematically compared these observations with fluid dynamic theory as well as with the theory that relates to lift propulsion in nature. I was especially interested in seeking reasons for what initially appeared to be unusual vortex formations that indicated propulsion was taking place in nonsteady flow.

Although airfoils are designed to develop steady flow, human swimming propulsion, because of anatomical restrictions, must employ directional changes of the limbs that cause nonsteady flow. I believe that skilled human swimmers, like birds, fish, and certain flying insects, are able to turn nonsteady flow to advantage by using dexterous movements that establish the necessary flow circulation through the rapid generation and shedding of vortices.

Chapter 5

Propulsive Mechanisms of Speed Swimming

The dynamics of all the swimming strokes cause fluctuating flow conditions because the continual directional changes of the hands are not conducive to maintaining steady flow. Although most skilled swimmers establish steady state propulsion with organized vortex systems at the beginning of a stroke, subsequent hand and limb directional changes quickly lead to a sequence of quasisteady to nonsteady periods. These changes are often difficult for some swimmers to accomplish without losing propulsion. However, underwater photography of skilled swimmers indicates that the shedding of large separate vortices occurs at approximately the same time as the hand's directional change.

In this chapter, we learn that propulsion in fluids is not limited to propellers and other purely mechanical means. To this end, we compare human swimming propulsion with the quick generating and shedding of vortices used by birds, flying insects, and marine animals in order to propel, and we find that human hands and feet function as swim foils using mechanisms similar to those common in nature. This information is applied directly to coaching a swimmer to use the reacting pressure resistance in the flow to generate quick propulsion through the water.

The Hand as a Swim Foil

A shed vortex indicates that a propulsive impulse in a particular direction has ended. World-ranked swimmers are invariably observed to shed a large vortex during a change of hand direction; these great athletes may be showing the ideal way to propel. Acceleration to top swimming speed requires sharp directional changes of the hand instead of the smooth, rounded transitions seen at slower speeds. However, vortex shedding before a propulsive impulse has ended is often a sign of inefficient technique.

Common causes of prematurely shed vortices are holding the hand too rigidly on the wrist or too sudden a directional change combined with excessive acceleration and application of force. In high-speed swimming every stroke consists of distinct impulses that accelerate with each change of hand direction. After a vortex is shed at the end of an impulse, a new vortex is quickly generated around the hand as it changes direction. Proof of this can often be seen in the subsequent shedding of the new vortex—albeit a somewhat smaller one—at the end of the stroke.

An Alternative Lift-Generating Mechanism

The quick generating and shedding of vortices just described is a propulsive mechanism prevalent in nature. This alternative lift-generating mechanism, unlike that of the conventional airfoil, is independent of foil shape and the existence of an ideal angle of attack. Instead, lift is established when a circulation (bound vortex) around the propelling member is superimposed on the general flow. (The role of flow circulation in lift propulsion is discussed extensively in chapter 4.)

Careful study reveals different types of vortex patterns in the flow field (figure 5.1). The vortex pattern developed depends on the natural aptitude of the swimmer and the speed at which the swimmer is moving. Drawings adapted from films confirm that an organized vortex system is longer at slower swimming speeds (figure 5.2).

High-speed swimming may cause sharp changes in hand direction with shedding of ring vortices at the end of each propulsive impulse (figure 5.2a). A large ring vortex is

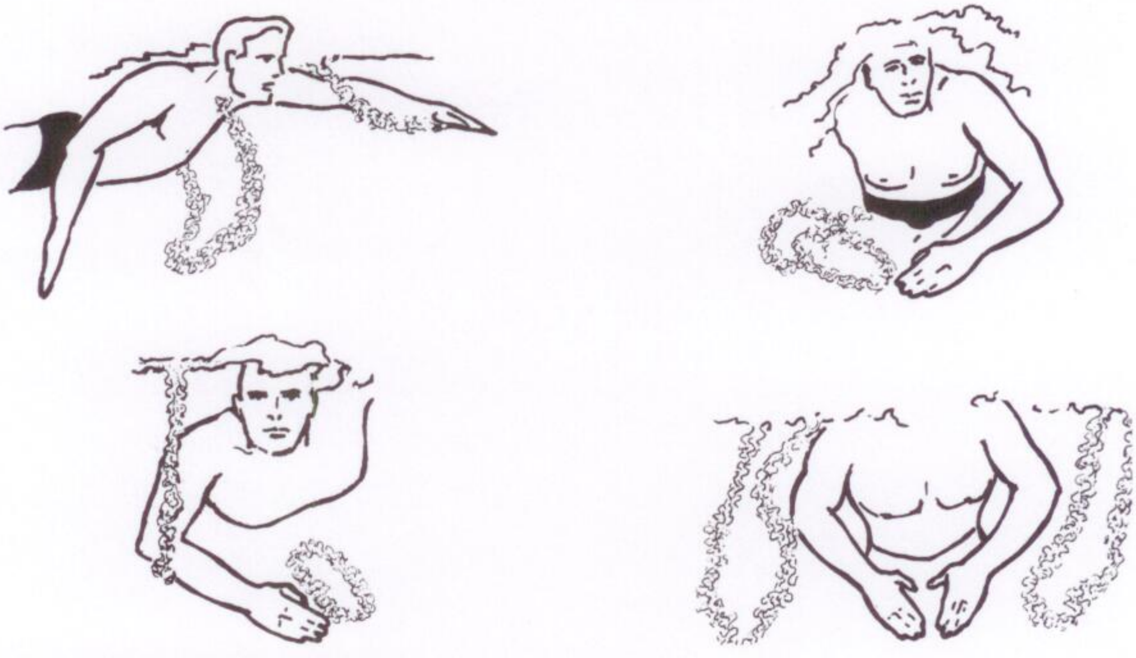


Figure 5.1 Different vortex patterns.

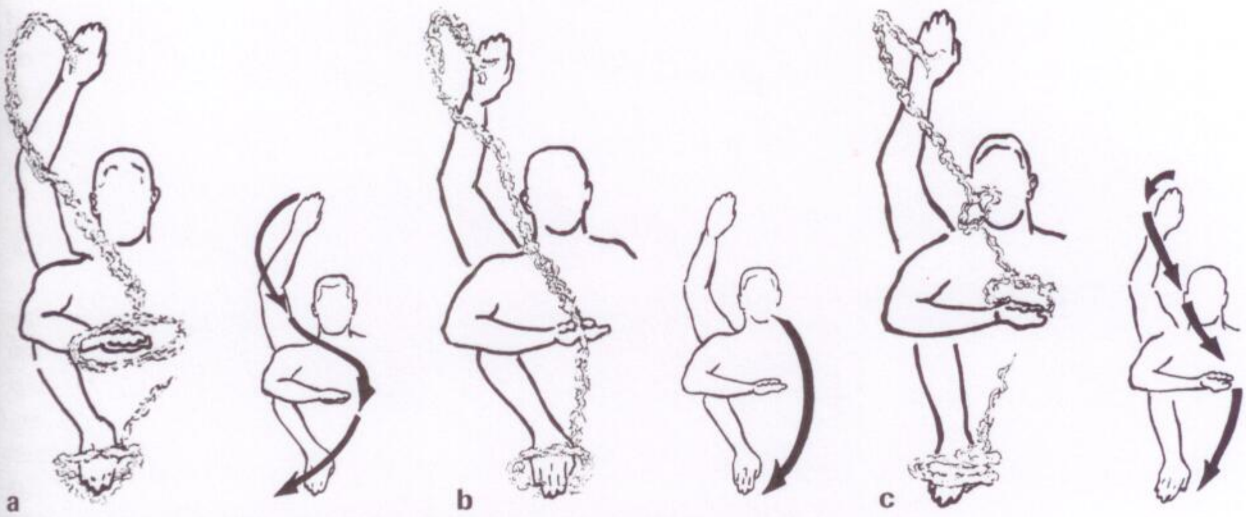


Figure 5.2 Vortex shedding reveals the effects of different stroke patterns.

shed as the hand changes direction in midstroke. The trailing vortices detach from the hand, indicating that the organized vortex system has ceased and that propulsion is no longer by foil-type lift. The remaining vorticity in circulation around the hand is shed at the end of the stroke by the fling-ring mechanism.

Smoother and rounder directional changes are achieved more easily at submaximal hand speed (figure 5.2b). Single-impulse propulsion and smooth hand acceleration help maintain an organized vortex system for most of the stroke. In the final stage of the stroke, the vortex trail becomes unsteady and starts to burst as a single vortex ring is shed by the fling-ring mechanism.

By applying excessive power or accelerating the hand too rapidly, even top swimmers may shed random vortices (figure 5.2c). Spasmodic vortex shedding represents kinetic energy lost to the water and is also characteristic of poor directional control of the hand. Excessive vortex shedding is common, which suggests that overapplying propulsive force and failing to accelerate the hand smoothly are more prevalent faults than generally recognized. These habits may account for subpar performance even when an athlete feels strong and powerful.

The Dual Function of the Hand

Although the literature contains frequent discussions of the elbow's changing posture during the swimming stroke, little reference is made to the articulation of the hand on the wrist. A swimmer who possesses a natural feel of the water uses the hand to perform a dual function by directing and channeling the flow circulation while also applying propulsive thrust. In fact, the dexterous functioning of the entire arm in an undulating fashion, almost in the manner of an elongated flipper, is quite noticeable. Talented swimmers show unusual dexterity, particularly during transitional phases of the stroke, and create remarkably consistent vortex patterns in the flow field.

Comparing Swimming to Propulsion in Nature

Comparisons between human swimming and fluid dynamic propulsion in nature are appropriate because the two share similar difficulties in coping with nonsteady flow. In fact, the similarities observed among the most diverse phenomena of fluid motion are not accidental but constitute a universal law of nature. Thus, it makes sense to compare examples from nature with human swimming propulsion.

Comparisons With Bird Flight

Lift-force propulsion is based on aerodynamic principles that originated in Lilienthal's (1889) intensive observations of bird flight. Similarly, it's highly probable that skilled swimmers use methods of developing lift (in conjunction with drag) during nonsteady periods of propulsion similar to those that occur in nature.

Aircraft and the majority of flying creatures fly in what might be called a standard way, using well-understood aerodynamic principles. But small birds and flying insects fly in a manner that can't be explained in simple aerodynamic terms. We know that aircraft depend on airfoils that move through the air steadily. Nonsteady flows around aircraft wings must be minimized because they reduce flight efficiency. In contrast, nonsteady aerodynamics are an inherent feature of natural flapping flight.

The subtleties of oscillating, or flapping, wing movement are still not fully understood, but bird flight in its simplest form—gliding or soaring—does not require flapping or the consumption of muscle power. Simply by stretching out the wing, the outer part merges with the arm section to form a continuous plane so that the bird flies in a manner similar to a fixed-wing aircraft. This use of steady flow is similar to the way in which a swimmer spreads the arms sideways during the beginning phase of the butterfly and breaststroke arm actions.

The spreading of the arms is one of the most economical movements in swimming, particularly in the butterfly stroke. It's also a remarkable simulation of natural flight. In fact, I like to instruct young swimmers to imagine they are giant condors with wings outstretched, launching themselves from a high cliff into an oncoming sea breeze. When the start of the butterfly arm stroke is properly timed, this form of *subaqueous flying* (a term sometimes used to describe sea-lion propulsion) develops high body velocity and is aided by the momentum developed a split-second earlier from the downward thrust of the dolphin kick, another derivation from nature.

This steady flow phase of the arm action is present at the beginning of all four swimming styles. During this phase, an organized vortex system is in place, as shown by the presence of tip vortices coming off the hands. As the stroke changes direction, however, it becomes difficult to maintain steady flow and to continue to use the hand in an airfoil fashion. This is also true of the flapping (oscillating) wing. Because of anatomical structure, birds and insects are unable to maintain a constant production of lift.

Until recently, standard aerodynamics had failed to explain how birds and insects overcome these handicaps. But, with the help of high-speed photography, the mystery is now near a solution.

The Rapid Generating and Shedding of Vortices

Birds and insects apparently employ mechanisms that swiftly establish air circulation around their wings, entailing the rapid generating and shedding of vortices. By so doing, they are able to generate lift more quickly than would be possible in steady airflow. This discovery cast an entirely new light on the problems that had long perplexed observers of bird and insect flight. The examples of aerodynamic propulsion in nature provide valid comparisons with human swimming propulsion, which also has to cope with the problem of propelling in nonsteady flow.

Unsteady Flow in Nature

Most of our present knowledge of the flying characteristics of birds and flying insects has been gained by direct observation, aided by slow-motion photography. Their motion bears an interesting comparison to some phases of human swimming propulsion, most notably the butterfly arm action, which uses directional changes of the hands in a path transverse to the swimmer's forward direction. When this type of arm action is accompanied by a marked degree of hand-forearm rotation, it is probable that the necessary flow circulation is produced for predominant lift-force propulsion to occur. When observing propulsion in unsteady flow in nature, it is important to note that the necessary bound vortex is created by mechanisms that operate intermittently in timing with the directions of the oscillating wing. As each propulsive impulse ends, a vortex is shed.

An expert swimmer propels by means of directional changes of the hands, which cause the rapid generating and shedding of vortices. In butterfly and breaststroke, this mechanism is probably similar in principle to the oscillating wing but only to the extent that the quick changes of hand direction generate the flow circulation necessary to produce lift-force propulsion. But, there the similarity to bird flight ends. Apart from possessing a basically similar skeletal structure, the human arm bears not even a remote resemblance to a bird's wing, nor does it flap while it propels.

Comparisons With Propulsion of Marine Animals

Marine animals, fish, and birds are highly specialized for propulsion in their respective fluid mediums. At the outset, we may find it difficult to imagine how the human swimmer could possibly adopt any examples at all from nature, but consider the dolphin kick used in the butterfly stroke, developed in 1935 by Jack Sieg and his coach David Armbruster. Based on the movement of the dolphin's tail, the dolphin kick represents the most effective attempt so far by humans to adopt a swimming technique from nature. Yet, despite the natural ease with which the dolphin kick fits in with the butterfly arm action, certain limitations in the human physique prevent the butterfly swimmer from completely emulating the harmonious locomotion displayed by the dolphin.

The main difference between the natural action of the dolphin and the acquired dolphin kick of the human swimmer is that the dolphin can perform the upbeat of its fluke, or tail, more quickly than the downbeat. The upbeat of the dolphin fluke is also faster than the upbeat of a swimmer's feet at equal movement frequencies. This is because the dolphin's musculature is more suited to producing a stronger movement on the upstroke of its fluke. The traces of the dolphin's fluke appear to be more symmetrical than those of human swimmers (Ungerechts 1983).

Comparisons With the Flight of Flying Insects

The most fascinating aerodynamic discovery of recent times has a counterpart in nonsteady swimming propulsion. It concerns the novel lift-generating mechanism used by some flying insects (Lighthill 1973). Aerodynamic calculations have shown that some insects are unable to generate enough foil-type lift to remain airborne. Their unique lift-generating mechanisms instead depend on means different from those of ordinary foils; the actual shape of the foil is of little importance. What is needed is an elongated body that carries a bound vortex and is moved relative to the stationary fluid. It does not involve refined adjustments of the angle of attack but does require rapid control of the flow over the tip of the foil.

The Clap-Fling-Ring Mechanism

Some flying insects use a clap-fling-ring action of their wings, which circulates air to form a vortex on each wing tip (figure 5.3). At the end of the downstroke these two vortices are shed

Figure 5.3 Clap-fling-ring mechanism of butterfly flight.

in a flinging action and combine to form one large vortex ring directly beneath the insect. The force needed to create the ring sustains the insect's weight.

The difference between a normal airfoil and the nonsteady fling-ring mechanism is that the vortex patterns leading to circulation are created prior to and independent of the movement of the foil through the fluid (Weis-Fogh 1973).

The Fling-Ring Mechanism in the Dolphin Kick

Obviously it is impossible for human swimmers to perform the clap phase that precedes the fling-ring mechanism. However, they may use similar mechanisms during nonsteady swimming propulsion. A typical example can be seen in the power dolphin kick when used at maximum effort. (The kick in the following description should not be confused with the gentler action of the soft dolphin kick, often used in the 200-meter event, which is more like a foil operating in steady flow.)

The power dolphin kick requires a rapidly established vortex circulation, in this case around the feet, prior to commencing the propulsive impulse. This is accomplished in a manner slightly different from the clap-fling-ring mechanism used by some flying insects.

In the absence of the preliminary clap phase of the mechanism, the soles of the feet set up the necessary preliminary circulation as they touch the surface of the water prior to the feet starting downward. The contact by the soles with the surface water sets up a surface tension caused by molecular attraction between the two fluids, water and air. As the feet thrust downward, a bound vortex forms around each foot. These vortices combine to form one large vortex ring that is shed in the vertical plane as the feet complete a powerful downward thrust (figure 5.4). The large size of the ring indicates that a large mass of water has been acted on, whereas the velocity of the water has remained relatively low. One indication of the dolphin kick's effectiveness is the distance between the regularly spaced vortices: The greater the distance between each shed vortex ring, the more effective the kick. I have often asked butterfly swimmers to swim a few strokes and then stop and look back underwater at their still-visible vortex trails. They were fascinated that they could actually see the result of their propulsion.

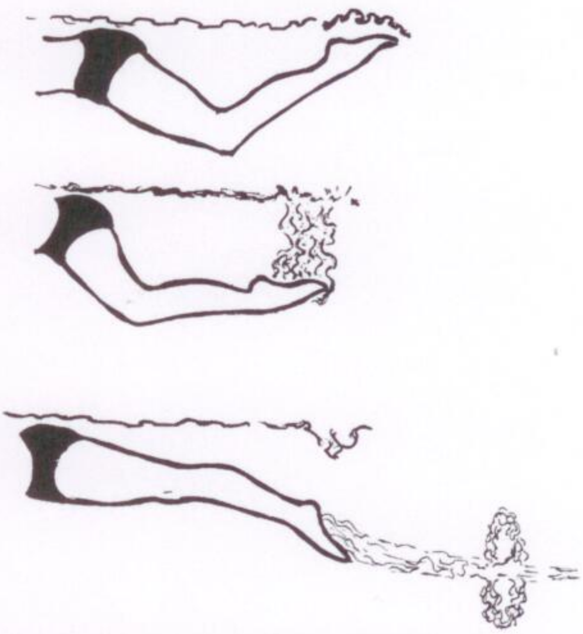


Figure 5.4 The fling-ring propulsive mechanism in the power dolphin kick.

Sometimes, when a swimmer's feet have spread too far apart during the downward thrust, two smaller vortices, one from each foot, will be shed. The effectiveness of this action is not as great as when a large single vortex is shed.

The use of the fling-ring lift effect in the power dolphin kick depends largely on a swimmer's ability to hyperextend the ankles and feet quickly to establish surface tension. Circulation results from the impulsive force created by the feet as they separate the air-water boundary.

The Fling-Ring Mechanism in the Two-Beat Crawl Kick and the Breaststroke Kick

Crawl swimmers using a power-producing two-beat kick also employ the fling-ring mechanism. Shed vortices of a smaller size can often be observed in the vertical plane behind each foot as it completes its downward thrust. For instance, this effect can be seen in the women's 1,500-meter event, in which the use of the two-beat kick usually predominates. Each swimmer in the race often leaves a ladder of small separate vortices trailing in the lane behind her.

Underwater movies of breaststroke swimmers show that the essential preliminary flow circulation is set up by the dorsi-flexion of the feet, combined with their change of direction, as they move from recovery into the propulsive phase. That the breaststroke kick uses the fling-ring lift mechanism can be seen when a breaststroke swimmer misjudges the depth of a push off from a turn and inadvertently introduces air into the kick. The resultant aeration of the flow reveals vortex rings behind each foot as the first kick off the wall is completed, a clear demonstration that the kick uses the fling-ring mechanism.

Practical Application of Flow Analysis as a Coaching Tool

The following discussion is couched in question and answer format. I am frequently asked these questions in conversation and correspondence.

What is a vortex?

A vortex is a mass of fluid that rotates about an axis. The axis of the vortex may be in almost any plane from vertical to horizontal.

What causes a vortex to be shed at the end of a propulsive impulse?

The presence of a bound vortex is essential for lift to occur. When a starting vortex is formed, it causes a bound vortex to be closed around a foil. Because a flow does not contain any circulation at the beginning of a stroke, it must not contain any circulation at the end of a stroke.

For example, experiments with a rotating cylinder in a flow channel show the reappearance of the starting vortex, now rotating in the opposite direction, once the flow is switched off and circulation has ceased. Right at the end, the starting vortex reappears, almost like a movie film played in reverse.

Similarly, it can be seen that a vortex must be shed if the hand is brought to a complete stop with respect to the local flow because there is no longer a mechanism producing and maintaining circulation. So, during a swimming stroke, when the hand stops or completes a propulsive impulse in a certain direction, whatever circulation is bound on it is shed to form a vortex ring.

The reader can easily demonstrate these phenomena. Stand in shallow water, dip your hand into the water, and move your hand; the rapidly formed starting vortex appears. Now end the movement by stopping the hand suddenly, which causes a shed vortex visibly whirling away rapidly from the hand.

What is the ideal shape of a shed vortex?

A shed vortex should be circular rather than elongated because a circular vortex acts on a larger area or mass of fluid. Its velocity is slower than that of an elongated vortex, which acts on a smaller area and a smaller mass. Although an elongated vortex (long loop) produces a flow causing forward thrust, this is not the most efficient mode of propulsion, for the reason just stated. The elongated vortex usually results from predominant drag propulsion when the hand is pulled straight backward like a paddle instead of in a curved path like a foil (figure 5.5). The vortex is shed from both sides of the hand and arm and appears early in the stroke.

What should be the ideal plane of a shed vortex?

Refer to the example of the circular vortex and assume, for the time being, that we have a swimmer who can produce this perfectly shaped circular vortex. Again, a vortex is a mass of fluid rotating about an axis that may be in almost any plane. Let us orient the plane of this circular vortex at different angles, from vertical to horizontal.

When the plane of this circular vortex is vertical and its axis is horizontal, all the fluid

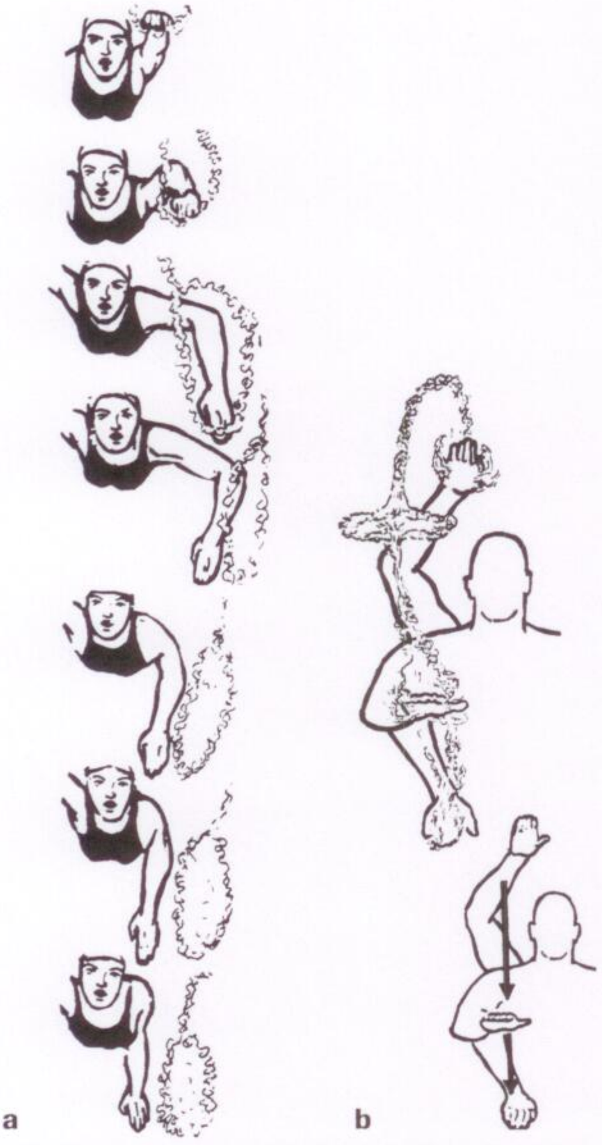


Figure 5.5 Predominant drag propulsion: flow reactions. *(a)* The flow reaction shows drag force propulsion resulting from pulling directly backward. All organized vorticity is shed very early in the stroke. *(b)* The typical lasso-type vortex consists of a short vortex trail attached to a large ring. The stroke is completed with wake turbulence behind the hand. Sometimes this action is shown by early detachment of the trailing vortex without the presence of a ring.

particles the vortex acts on will be moved in the stream direction (the horizontal direction), which results in ideal direct forward propulsion. When the plane of the vortex is horizontal, or lying parallel to the surface of the water, all the fluid particles that this vortex acts on will be directed downward, meaning that the net force created by the swimmer is upward rather than forward.

The conclusion is that if a swimmer's stroke is efficient, the plane of the shed vortex tends to be vertical or nearly vertical. The more vertical the vortex plane, the more likely the propulsive impulse has generated near maximum forward thrust.

What do different size vortices in the flow field tell us?

Counsilman (1971) states that it's better to move a large mass of water a short distance than to move a small mass of water a long way. In terms of propeller theory, this idea could be expressed as "it's better to move a large mass of water slowly than to move a small mass quickly." Stated thus, the principles of propeller theory apply directly to swimming propulsion.

In another of his prominent studies, Counsilman (1980) showed that skilled swimmers produce marked hand acceleration in the latter phase of the crawl, a finding borne out by analysis of the flow reaction. A smaller vortex appears after the end of the stroke, whereas a larger vortex appears during the stroke, when the first propulsive impulse of the stroke is completed (as the elbow reaches maximum flexion). The smaller vortex at the end of the stroke shows an increase in the flow velocity caused by the hand's acceleration.

It may be that the first, larger vortex creates a new flow direction and the hand may have to move faster to make maximum use of the new flow velocity. The skilled swimmer may be aware of this—albeit subconsciously—and adjust the hand accordingly.

What does the presence of excessive vorticity mean?

A coach can learn a great deal from a swimmer's subjective comments, especially immediately after a race. Sometimes, when a swimmer has turned in a particularly fine performance, the swimmer may say, "I felt so good that I could have gone faster," or, conversely, a swimmer may express disappointment at a recorded time by saying, "I felt so strong and powerful—I can't understand why my time wasn't faster."

As has been observed underwater, very powerful swimmers often shed vortices in the middle of a propulsive impulse, which shows they are exerting more power than necessary. In contrast, the swimmer who finishes with power in reserve, feeling it was possible to go faster, perhaps instinctively has not overapplied power.

There could be another reason for excessive vortex shedding, however. As the hand exceeds the ideal angle of attack (in terms of the conventional airfoil mechanism), the flow separates, destroying the circulation. At this stage a swimmer will start to use unconventional propulsive mechanisms to propel in the resulting unsteady flow. One reason for excessive vortex activity, then, could be that the swimmer can no longer adjust the hand incidence so as to maintain airfoil-type propulsion and thus has to shed the existing flow circulation to establish a new flow around the hand.

Why is it not always possible to see the swimmer's flow reactions in the water?

The presence of visible flow reactions depends on accidental air entrapment. Aeration is a recognized visualization technique used by fluid dynamicists. Although most swimmers produce a visible flow reaction when swimming at speed, no procedure ensures regular visualization of the surrounding flow field. Several flow visualization methods are used to analyze the flow around models in flow channels and wind tunnels, but the use of dyes, lasers, smoke, and so on could pose a safety hazard for swimmers. Up to now, photography, especially shadow photography, has provided promising results.

The flow patterns of great swimmers at key phases of propulsion are remarkably predictable. When observing these top performers, it's not difficult to form a synthesis of the flow patterns that can be anticipated. Nevertheless, we lack a sophisticated method of flow visualization that enables vortex reactions to be measured accurately against a grid. Ideally, such a method would require front- and side-view photography of swimmers at racing speed. The side views should be photographed by an underwater camera moving on a track and kept constantly abreast of the swimmer; where access to a swimming flume is available, the swimmer could be filmed while tethered in an oncoming flow. Comparing the results produced by the two approaches would add another dimension to flow analysis.

Should swimmers entrap air into their strokes to make the flow reactions visible?

Intentional aeration is not a good idea because under certain conditions, air entrapment can cause bursting bubbles that may increase drag. Although air entrapment should not be encouraged, the introduction of a bubble can improve efficiency sometimes, when a bubble attaches to the upper surface of a foil, causing a modified contour that prevents massive separation of the flow.

Shaping the Flow

Little is known about the effects of body shape on a swimmer's efficiency. The bulky, squat body type has not been as prevalent in competitive swimming as it once was. Most of the leading swimmers, irrespective of their events, are tall and lithe, with a lean physique like a basketball player's. Their muscles tend to be long rather than short and heavy like a weightlifter's.

The effects of a swimmer's shape and physical proportions on speed and efficiency are governed by the ratio of height to bulk, among other important factors. The more slender the swimmer, the less the underwater volume compared to the swimmer's height, or length, in the water. If a swimmer has a gradually tapering physique, water will flow past more easily. Other variables include buoyancy, body composition, flexibility, neuromuscular patterns, and individual aptitude.

However, the shapes of certain human body types (somatotypes) are at a distinct disadvantage in speed swimming. Observation of the water's flow reactions around individual swimmers confirms this.

Some swimmers have extreme difficulty controlling the oncoming flow of water along the entering arm(s) with sufficient continuity to obtain the best timing of the stroke. The more successful swimmers appear to be favorably endowed by nature with streamlined body profiles and functional limb shapes that enable them to continuously control the oncoming flow between one stroke and the next.

In all four styles of swimming, the arms at the start of the stroke should act much like the bow of a ship, channeling the oncoming flow along each arm and around the body.

The crawl permits a skilled swimmer to smoothly control the oncoming flow as one stroke ends and the next one commences. The overlapping arm action of the crawl stroke allows a swimmer to feel the oncoming flow of water advance along the entry arm at the same time as the opposite arm is unswirling the flow from the hand and forearm at the finish of its stroke. The expert crawl swimmer is thus able to control simultaneously two separate flow reactions during this fleeting but critical timing phase of the arm stroke.

Compared to the crawl, the other three swimming styles—backstroke, butterfly, and breaststroke—produce oncoming flows a swimmer cannot so easily intercept and translate into smooth continuous propulsion.

In the back crawl, the arms remain almost the same distance from each other during the complete stroke cycle and do not overlap as much as in the crawl stroke. So, unless a backstroke swimmer has a tall, lean body and an arm reach long enough to control the oncoming flow efficiently at entry, accurate timing between the entry arm and the finishing arm is more difficult than in the crawl.

In efficient crawl and backstroke swimming, the alternating action of the arms ensures that at nearly every stage of the stroke cycle one arm extends forward at entry to intercept and smoothly channel the oncoming flow while the other arm completes its stroke. In butterfly and breaststroke, however, because the arms move simultaneously, such nearly constant interception of the oncoming flow at entry is not possible. Moreover, some butterfly and breaststroke swimmers have difficulty controlling the oncoming flow around the arms at the beginning of each stroke because the momentum necessary to produce this oncoming flow depends on accurate timing between the arm and leg actions.

Exploiting Examples From Nature

I have described how humans developed their admittedly limited swimming ability. Through considerable invention and the gradual acquisition of increasing skill, we learned to adapt our comparatively awkward land-living bodies for efficient use in water.

Earlier, I made a comparison between human swimming and similar propulsive mechanisms in nature. Is it possible to improve the efficiency of human swimming by seeking out and adopting further examples from nature? Can we learn to use propulsive mechanisms and postural shapes derived from nature to provide a more facile, dexterous, and efficient mode of swimming?

Although probably no further adaptation from nature will have the same dramatic effect on the sport as the development of the dolphin kick, we can learn much by studying fish and birds, their natural shapes, and the changing shapes they adopt during various phases of propulsion. Much of their efficiency can be attributed to their skill in making smooth transitions from the end of one propulsive impulse to the start of the next. Unfortunately, the subject of transitional phases of the stroke in human swimming has yet to studied.

Ideal Postures and Shapes

The literature contains little mention of the possibility of ideal postures or shapes of the hand in relation to the wrist as the arm moves through the changing phases of a swimming stroke.

A better understanding of how to shape the hand-wrist posture during the arm stroke could improve swimming efficiency. This applies to the postures assumed by the hand and wrist in relation to each other during the propulsive impulse, at the end of the propulsive impulse, and during the transitional phase between the end of one propulsive impulse and the start of another.

Birds and fish exhibit shapes adapted to their function, and they are able to change their body forms somewhat to alter the flow reactions around their bodies. A study of the shapes and changing forms adopted by fish and birds may have beneficial applications for human swimming.

Careful study of the arm posture of an expert butterfly swimmer during the inward sweep of the stroke (figure 5.6) indicates that the swimmer, probably without knowing it, has adopted two characteristic shapes common in nature:

1. The projecting thumbs each act like an alula, or small extra wing.
2. The hand and forearm, from the tip of the little finger to the point of the elbow, assume a lunate, or crescent-shaped, configuration.

Both shapes are concerned with lift enhancement in that they help keep the flow attached to the hands and forearms. Some butterfly swimmers who keep their thumbs pressed in and their hands in a straight line with their forearms encounter flow separation very early in the stroke. The vortex patterns set up by the swimmer in figure 5.6 show that she has kept the flow attached to her hands and forearms even though her hands have already changed direction from their initial outward sweep and are well into the inward phase of the stroke. The only visible signs of pending flow separation are slight swellings in the vortex trails near the fingertips.

The Alula Effect in Smoothing Out the Flow

In bird flight, the alula, sometimes referred to as the bastard wing, is an interesting refinement that acts as a subsidiary airfoil in front of the leading edge of the main wing. Under normal flight conditions, the alula is folded back out of the way. As the bird approaches stalling speed, however, and the airflow over the upper wing surface becomes turbulent, the

Figure 5.6 Arm posture of expert butterfly swimmer.

alula is spread forward to form a slot through which air rushes, restoring a smooth, fast airstream and curtailing stall (figure 5.7). In similar fashion, when a swimmer's hand is inclined at too large an angle of attack to keep the flow attached to the hand, the thumb, when held away from the hand, produces a throttle effect through which the speed of the flow increases, creating a low-pressure area on the knuckle side of the hand that produces more lift and a smoother flow around the hand.

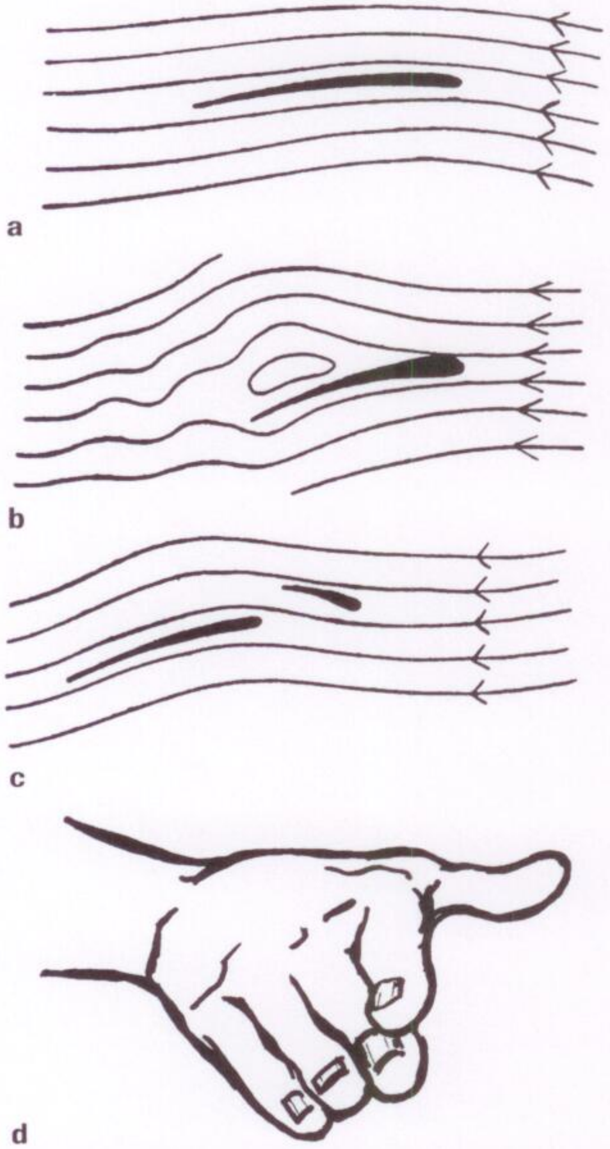


Figure 5.7 Use of alula mechanism to create steady flow. *(a)* Foil in steady flow. *(b)* Steep angle of attack produces unsteady flow. *(c)* Alula restores steady flow. *(d)* The thumb used as an alula.

The Efficiency of Lunate, or Crescent-Shaped, Contours

The wings of seagoing birds such as shearwaters and albatrosses, which spend an enormous amount of time in the air, are swept backward. Even the limbs of species adapted to propulsion through water (a fluid, just as air is, and thus subject to many of the same physical laws) show the same crescent shape, particularly the tail fins of fish such as marlin and tuna and marine mammals such as dolphins and whales (van Dam 1988; figure 5.8).

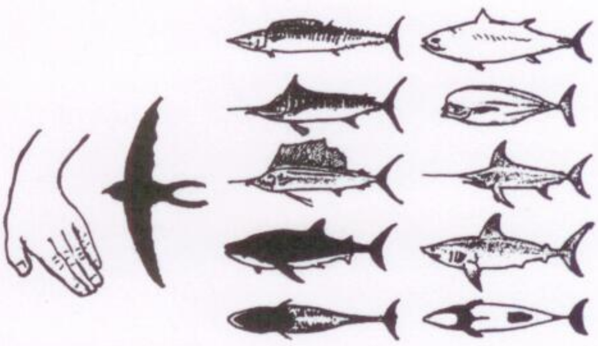


Figure 5.8 The ulnar-flexion of the wrist in the human swimmer resembles various lunate shapes in nature.

Does the crescent shape bestow some special advantage? Only recently, with the development of computerized modeling techniques that faithfully represent the dynamics of vortex wakes, was it discovered that the most aerodynamically efficient shape is not the conventional flattened ellipse. A half-moon planform, like that of a whale's tail, with a curved leading edge and a straight trailing edge is superior, and a crescent planform, in which both edges curve backward like a swift's wing, is more effective still.

These shapes enhance performance because the vortices that form at the trailing edge of the inboard section of a curved wing or fin wash downward (sideways for a fin) ahead of those further along the limb, producing updrafts and sidedrafts that like miniature hurricanes, agitate nearby fluid particles.

The tip of a wing or fin acts in turn like a sail, converting some of the kinetic energy of these spiraling streams into forward thrust. In this manner, a crescent planform generates at least 10 percent less induced drag than an elliptical one, a reduction that grows in significance as the time an animal spends flying or swimming increases.

In the human swimmer, the ulnar-flexion of the wrist in relation to the forearm creates a crescent-shaped contour that keeps the flow attached around the hand and forearm. This is important because if the flow were to separate from forearm and hand, drag would increase. In fact, some swimmers who changed to an ulnar-flexion of the wrist during the inward sweep of the arm reported increased ease in this phase of the stroke without experiencing loss of propulsion (figure 5.9).

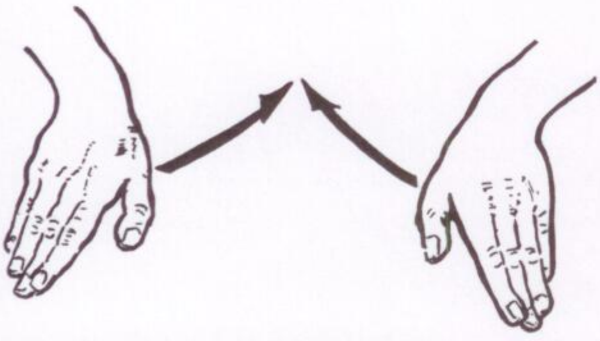


Figure 5.9 Ulnar wrist flexion on inward sweep of the hand.

The discussion so far has centered on the effect of ulnar wrist flexion during the inward sweep of a swimming stroke, but what are we to make of the ulnar wrist flexion sometimes seen during the outward sweep of a swimming stroke? In addition to assuming the crescent-shaped contour of the lower arm, some swimmers also incline the hand slightly upward during the outward sweep so that the fingertips appear to be the highest part of the entire arm.

The outward arm sweep of champion butterfly swimmer Mary T. Meagher is a good example of this action (figure 5.10). The slight upward tilt of her hands is not unlike that of a large soaring bird turning up its wingtip primary feathers to reduce drag induction. In other swimmers, the elbows are pronouncedly higher than the hands, which in turn are set at a sharp angle from the wrists to shape the whole arm remarkably like a cantilevered hydrofoil. By making models of the functional arm shapes of talented swimmers and testing them in flow channels, it should be possible to analyze the exact effects these shaping techniques have on the surrounding flow field. It would also be possible to measure at what angles of attack flow separation (and consequent vortex shedding) takes place.

Figure 5.10 Outward arm sweep of champion butterfly swimmer Mary T. Meagher. The fingertips appear to be the highest point of the entire arm. Adapted from instructional film by Maglischo and Gambril, produced by First Essex Productions.

Midstroke Transitions

Even at topflight swim meets it's common to see swimmers whose techniques are based too much on tugging, pulling, and pushing, which are essentially land-type concepts. Many swimmers try to pull directly through the hard part of the stroke instead of adopting transitional postures of the hand that would enable them to more easily control the oncoming flow.

We might possibly learn something from observing the transitional shapes adopted by certain reef fish when maneuvering. Their fins move through a very flat angle as they fan around to a new posture in a helicoidal path. Fish do not waste energy by trying to overcome a developing or increasing resistance such as that encountered by a human swimmer as the elbow reaches maximum bend in midstroke and the hand reaches an angle almost perpendicular to the line of forward progression. The spiraling fin of the reef fish simply goes around the obstacle of increased resistance.

Perhaps the human swimmer could copy this action, when swimming crawl, for example. In midstroke the forearm is medially rotated so that the hand is turned slightly, as shown in figure 5.11. The transition is made with a quick, deft movement. The palm of the hand is turned to face slightly forward, almost like turning a vertical slat in a venetian blind. The motion quickly presents the hand at a more acute angle with less drag as the hand and forearm round out to finish the stroke with a fanlike action (figure 5.12). A biomechanical study of this suggested midstroke transitional maneuver, performed by a skilled swimmer, could prove interesting and enlightening.

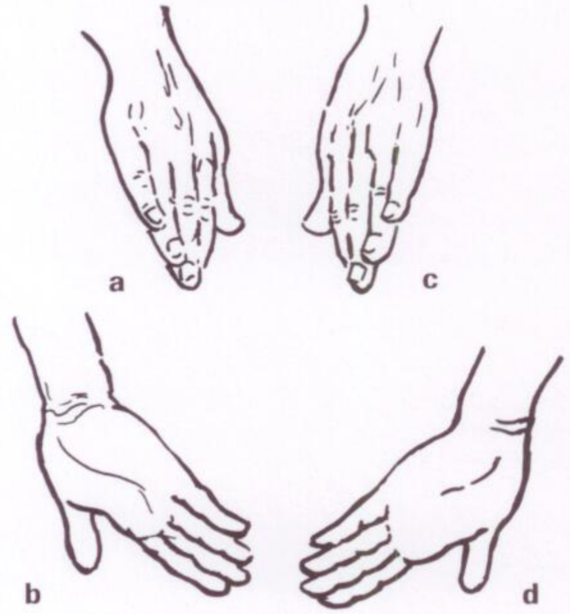


Figure 5.11 Midstroke transition showing four views of medially rotated hands in the crawl stroke: *(a)* top right view, *(b)* bottom right view, *(c)* top left view, and *(d)* bottom left view.

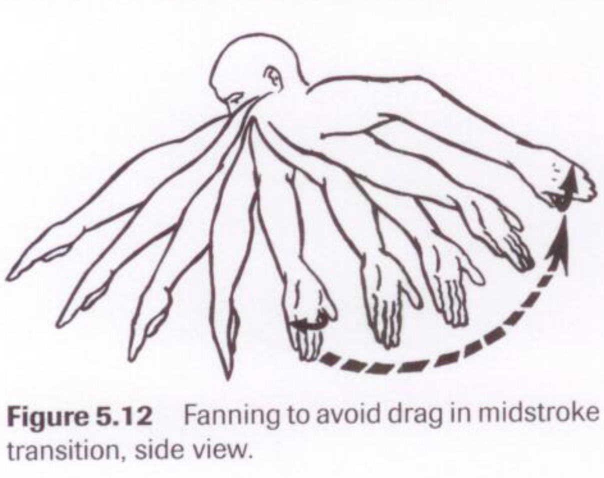


Figure 5.12 Fanning to avoid drag in midstroke transition, side view.

Functional Shaping as a New Approach to Stroke Technique

The purpose of this chapter has not been to recommend dramatic new changes in technique but rather to show how efficient propulsion depends on adroit manipulation of the reacting flow.

Underwater photography shows that talented swimmers use a variety of hand, finger, and thumb configurations during the changing phases of a swimming stroke (figure 5.13). It is highly unlikely that any one swimmer could incorporate all these principles within an individual stroke pattern, nor is it recommended that a swimmer attempt to do so. How should a coach approach teaching the various shaping techniques such as the alula effect, the ulnar wrist flexion, hand cupping, and so on? Each person should experiment to find which of these techniques can be comfortably used within his or her personal swimming style. For example, whereas one swimmer may feel an advantage is gained by assuming a lunate shape between hand and forearm, another swimmer may feel more comfortable keeping the hand aligned with the forearm. The coach's role will not be to enforce these finer embellishments on a swimmer but to recognize their value and not intervene when a swimmer uses them naturally.

Traditional coaching methods have focused on establishing desired stroke patterns but have neglected to provide the swimmer with adequate feedback on the efficiency of performance. Children should be taught flow recognition and manipulation from an early age. They should be made aware of functional shaping of the hand and arm as important aspects of technique. Learning to create, feel, and recognize the ideal reacting flow of the water gives swimmers instant feedback on the efficiency of their swimming strokes.

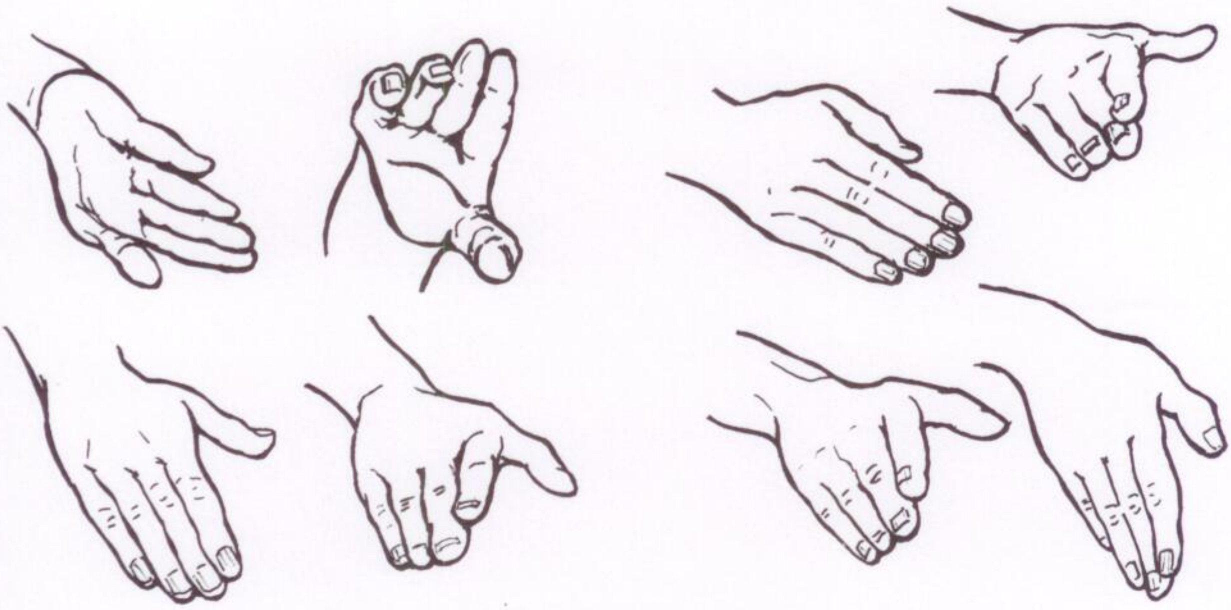


Figure 5.13 Various hand-digit postures used by talented swimmers.