



## Newton to Bernoulli and Back Again by Dr. Ernie Maglischo (1995)

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Dr. Ernie Maglischo has coached swimming for 30 years on the college and age group levels. In twenty-one (21) years of college coaching his teams have won 13 NCAA Division II championships and 19 Conference Championships. He is the only coach in NCAA history whose teams have won NCAA championships at three different universities. An internationally known expert on the stroke techniques and training of competitive swimmers, he has been selected NCAA Division II Swimming Coach of the Year on six (6) different occasions. He is presently in his third year as men's swimming coach at Arizona State University. Ernie has authored two textbooks on swimming and co-authored one text on nutrition for athletes. He has authored five books on swimming and training. His latest is *Swimming Even Faster*, a revision of his earlier work, *Swimming Faster*. Additionally, he has authored or co-authored over 43 periodical publications including reports of original biomechanical and physiological research. Recently, he and his wife Cheryl have developed three computer programs for competitive swimmers. Often a keynote speaker at international meetings, he has presented papers on the

technical aspects of competitive swimming in over 16 different countries and 28 states across the U.S. His academic training includes a Ph.D. in Physical Education with an emphasis in Physiology of Exercise from Ohio State University, an M.S. degree from Bowling Green State University and a B.S.Ed. degree from Ohio University. He is a member of the American College of Sports Medicine, and was appointed to the Educational Advisory Board of the Gatorade Sports Science Institute. In 1991 he was awarded the NATIONAL COLLEGIATE AND SCHOLASTIC SWIMMING TROPHY by the College Swimming Coaches Association. He is also a recipient of the Honor Award For Outstanding Contributions to Aquatics from the Aquatics Council of the American Association for Health, Physical Education, Recreation and Dance (AAHPERD).

## **INTRODUCTION:**

Through the years there have been many attempts to identify the physical laws responsible for swimming propulsion. Early attempts described the movements of swimmers hands as similar to those of an oar. Later, they were likened to the movements of paddles. Paddle propulsion was characterized as a straight-forward application of Newton's Third Law of Motion, the action-reaction principle (Counsleman, 1968, Silvia, 1970). That principle states that every action (force) of an object will produce a reaction (counterforce) of equal magnitude in the opposite direction. Consequently, the action of pushing water backward was believed to cause a reaction that propelled swimmers forward.

Swimmers were advised to apply this principle by pulling, then pushing their hands horizontally backward for the longest possible distance under the mid-lines of their bodies. This was supposedly done by first flexing their arms at the elbows and then extending them. An example of paddle propulsion is

illustrated in Figure 1a. The notion of pushing straight-backward was later amended to a weaving backward path when motion picture films revealed that swimmers' hands were moving in an "S" path around the mid-line of their bodies. The "S" stroke is depicted for a freestyle swimmer in Figure 1 b.

Attempts to depict stroke patterns, like those in Figure 1, were flawed because they showed the hands moving relative to a stationary body. They overlooked the fact that swimmers would go nowhere if their hands traveled back from overhead to a position at their hips.

In 1971 Brown and Counsilman sent shock waves through the competitive swimming community when they showed that swimmers used sideward and vertical sculling motions to propel themselves forward. In their landmark study, they filmed swimmers in a darkened pool with a light attached to their fingertips. This produced a record of hand movement relative to a fixed point in the pool. The stroke patterns revealed by these motion pictures were quite different from the ones in Figure 1. They showed swimmers making diagonal sculling motions with their hands moving laterally and vertically far more than backward. Typical stroke patterns of this type are illustrated in Figure 2. They provide a more accurate representation of the effect swimmers' hands have on the water than the patterns in Figure 1, and it is this effect which ultimately determines propulsion.

Brown and Counsilman believed these sculling motions were propulsive, which questioned the exclusive role of propulsive drag in swimming propulsion. They concluded, therefore, that swimming propulsion was also the result of lift forces similar to those at work during aerodynamic

flight. They further suggested that the Bernoulli effect played a major role in the production of these lift forces.

The validity of their theory has recently been questioned in at least two publications (Ferrell, et. al., 1992, Rushall, et. al., 1994). The purposes of this paper will be to examine the validity of the application of Bernoulli's Theorem to swimming propulsion and to examine the roles of lift and drag propulsion in swimming. Before attempting that examination, I would like to present a brief description of hydrodynamics so we have the same understanding of the terms involved.

## **THE DYNAMICS OF WATER FLOW:**

Undisturbed but moving water is usually depicted as laminated streamlines. These are horizontal streams of water molecules resting one on top of the other. Air particles have the same arrangement as water and research that applies to one also applies to the other. Even though water is 800 times more dense than air, both are fluids, consequently, the behavior of one can be used to describe the behavior of the other.

The behavior of fluids is usually studied by either suspending objects in a wind tunnel or water channel and pushing the fluids past them at known speeds, or by moving the objects through the fluids at known speeds. The flow of air or water is called **laminar** when all parts of these fluids are moving smoothly past an object in the same direction at uniform speeds. Figure 3 illustrates the laminar flow of smoky air past a foil (wing shape) suspended in a wind tunnel.

The movement of fluids, the forces acting upon them, and the forces produced are considered to be the same whether an object is passing through a fluid, i.e. a hand moving through the water, or when the fluid is pushed past a non-moving object. However, in the second case, hydrodynamic and aerodynamic experts will usually describe the movement of the fluid as **relative** to the movement of the object. The concept of relative motion is an important one because it allows researchers to study fluid dynamics under laboratory conditions with non-moving objects and draw accurate conclusions about field conditions where the objects are moving through the fluid.

The flow of fluids past an object is usually **laminar** or undisturbed if the object is traveling at a constant rate of speed and has a streamlined shape that does not disrupt the flow to any great extent. When objects with poorly streamlined shapes and constantly changing rates of movement travel through the water, they produce a condition of **disturbed flow** where the direction and speed of the water molecules around them may vary from moment to moment.

Lift theorists believe swimmers use their hands and feet (and arms and legs) like hydrofoils. For this reason, and because it makes explanations easier to understand, both airfoils and hydrofoils will be used to illustrate some additional concepts of fluid dynamics that apply to swimming propulsion.

The illustration in Figure 4 is an attempt to depict the relative flow of water around a foil. When the foil in Figure 4 moves through the water it intrudes

upon laminar streams immediately in front and to the sides of it. Those streams must first, separate to permit the object to pass through, and then close in behind it to re-establish their laminar arrangement. The disruption of the streams of water molecules in the path of the foil will cause resistance to its movement. The term for this resistance is **drag**. Drag can be defined as a force that opposes motion, therefore, *it always acts opposite the direction an object is moving*.

The foil in Figure 4 has a very good shape for reducing drag as it moves through water. Its tapered front, or **leading edge** intrudes upon a small number of laminar streams and it pushes them up and out of the way in a gradual manner so that they experience minimal disruption. Once the object passes through a particular section of water, the pressure of the water both above and below cause the streams that were closest to the object to “fill in” behind it. In the case of the foil in Figure 4, its tapered rear, or **trailing edge** permit the streams to return to their original positions almost immediately after it passes through.

## **DRAG FORCES, LIFT FORCES AND BERNOULLI'S THEOREM**

**Drag forces.** What was just written should not be taken to mean that the relative flow of water around a foil is completely laminar. When objects move through the water, those molecules in closest proximity will come in contact with it. The friction between water and the surface of the object cause some of the molecules to literally “stick” to its surface forming what is called a **boundary layer**. The water molecules that make up the boundary layer are momentarily dragged along with the object causing them to collide with the molecules to the front and side of them. This, in turn, causes those molecules

to rebound in random directions creating what is known as **turbulence**. The boundary layer around a foil is illustrated in Figure 5.

The random motion of water molecules, many of which will be pushed backward and sideward, causes an increase in water pressure in front of the paddle. Consequently, a pressure differential is produced between the front of the foil where the pressure is higher and behind it where the pressure is lower. This pressure differential will exert a backward force on the foil since objects tend to move from areas of higher pressure toward areas where the pressure is lower. That backward force is responsible for the resistance or drag that the foil encounters. The direction of the drag vector is illustrated in Figure 5.

Drag forces are also an example of the application of Newton's action-reaction principle. In Figure 5, the sideward movement of the foil from right to left across the page constitutes the action and the drag force is the reaction.

As mentioned earlier, a wing-shaped object like the one in Figure 5 encounters very little drag force because it permits gradual and minor disruptions in the laminar streams of water it is moving through and because it permits those streams to, once again, become laminar almost immediately after it has passed through them.

Contrast the effect of the wing-shaped object in Figure 5 with that of the paddle-shaped object in Figure 6. The paddle is moving through the water

from right to left so that the leading edge is its entire flat front surface. Due to the large surface area it presents to the water, the paddle intrudes upon a large number of laminar streams at the same time. The effect is that the water molecules in those streams are displaced up, down and sideward to allow the paddle to pass through. In the process, they collide with an ever widening number of streams lying both behind and to the sides of them. The molecules bounce off one another creating some turbulence on the back side of the paddle. However, the pressure or resistance of the water to the movement of the paddle is high which keeps most of the fluid pushing against the paddle as the streams separate. (See figure 6.)

Once the paddle has moved through a particular section of water, the streams attempt to fill in behind to re-establish their laminar arrangement. This is not immediately possible, however, because of the large number of streams that were disrupted and because the trailing (back) side of the paddle is not tapered. The water molecules would have had to make a 90 degree change of direction as they passed over the paddle in order to fill in and reestablish laminar flow immediately behind it. This is not possible because the pressure of water both above and below the disrupted streams is not sufficient to “push” them in behind the paddle until they are considerably downstream. This leaves another area of turbulence behind the paddle where only a small number of water molecules are swirling.

The region of turbulence behind the paddle is commonly referred to as the **wake**. Water pressure is considerably lower in the wake because of the small number of water molecules that are whirling around in the area. As you would expect, the sudden and large increase of pressure that was caused by water disturbance immediately in front of the paddle interacts with the rapid drop in pressure caused by the failure of water to fill in immediately behind it

to produce a sizable pressure differential that greatly increases the drag force acting on the paddle.

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**Lift Forces and Bernoulli's Theorem.** Notice that the foil

in Figure 6 was facing perpendicular to the direction it was moving. As explained, this orientation produced a large pressure differential that created a drag or resistive force in the opposite direction. The situation changes when a foil is angled somewhat less than 90 degrees to the direction it is moving. For one thing, the direction of the pressure differential will not be opposite its direction of motion, and, for another, a second component of force will be exerted on the object at a right angle to the direction it is moving. The term for that force is **lift**. *Lift forces always act in a direction that is perpendicular to the drag force.*

Another foil-shaped object is used to illustrate lift and drag forces in Figure 7. Notice that the foil has a “cambered” or curved upper surface while the underside is straight. This makes the distance from leading to trailing edge over the upperside somewhat longer than underneath. The law of conservation of mass tells us that the fluid in the streamlines over the top of the foil must meet those on the underside when the foil passes through in order to prevent a vacuum from occurring. Since the distance over the top of the foil is greater, the relative flow of water over the top will be faster than that on the underside so that the streams can meet when the foil passes through.

This is where **Bernoulli's Theorem** comes into the picture. Daniel Bernoulli, an 18th. century Swiss mathematician, was the first person to recognize this

inverse relationship between changes in fluid speed and pressure. Simply stated, *the pressure of a fluid will decrease when its velocity increases and vice versa*. Consequently, since the fluid above the foil is moving faster, its pressure will decrease, producing a pressure differential between the underside of the wing where the pressure is greater and the upper side where it is lower. In simpler terms, the upward pressure below the foil will be greater than the downward pressure above and a “lifting” force will be exerted against the underside of the foil in the direction of the area of low pressure. The term lift is an unfortunate choice for this force because it implies motion in only one direction, upward. In actuality, lift forces can be exerted in any direction that is perpendicular to the direction of drag. The direction in which lift and drag forces operate is usually represented, as it is here, by vectors. The magnitude of these two forces is represented by the length of those vectors.

The illustration in Figure 7 may have given the false impression that a foil shape is necessary for the production of lift forces. Actually, the orientation of an object plays a much greater role in the creation of both lift and drag forces. This orientation is referred to as the **angle of attack**. It is the angle formed by the inclination of the object to the direction it is moving.

The angle of attack cannot be too small nor too large or the magnitude of the lift force will be reduced. Both lift and drag forces are lowest when the angle of attack is 0 degrees. Increasing the angle of attack from 0 degrees will produce more lift force initially. However, lift will be reduced and drag increased when the angle exceeds a certain optimum value. The airfoil shapes in Figure 8 demonstrate the effect on lift forces of angles of attack which are both too small and too great.

The foil in Figure 8a is a replication of the airfoil in Figure 7. It is moving across the page from right to left at an angle of attack which is too small to produce significant amounts of either lift, or drag forces. This is because it “slips” through the water on its edge without disturbing very many laminar streams. As a result, the pressure differential between its under and upper sides is not very great. Any lift force that acts on this foil is due entirely to its shape and surface friction.

The foil in Figure 8b is pitched upward at an angle of attack which is approximately 12 degrees to the direction it is moving across the page. This is an excellent angle of attack for a wing because it produces a significant increase in lift while keeping drag forces to a minimum. As you can see, the disruption of laminar streams is minimal. However, the slight angle of inclination causes the water passing over the top of the foil to meet its leading edge at lower point. Consequently, the streams passing over the top must travel an even greater distance to pass over the top of the foil in Figure 8b than they did to pass over the top of the foil in Figure 8a. The result is a faster flow of water over the top of the foil in Figure 8b relative to the speed of flow underneath so that the molecules can reach the trailing edge at the same time. Consequently, the pressure is reduced over the topside relative to the pressure underneath. This increases the pressure differential between the under and upper sides of the foil resulting in a greater lifting force.

The foil in Figure 8c demonstrates that lift forces are decreased when the angle of attack is too great. At first glance, this would seem to be advantageous to the production of lift because the water passing underneath the foil is being displaced downward to a considerable extent. However, the foil is tilted up so much that the water in the boundary layer cannot maintain its attachment to the upperside of the foil as it passes over the top. When this happens, the boundary layer is said to **separate** causing an area of low

pressure behind the plate where small numbers of water molecules are swirling around. Since the region of lowest pressure is now in the wake immediately behind the foil, the direction of the pressure differential is from its front to its rear, rather than bottom to top. As a consequence, the drag force opposing the foil motion increases tremendously while the lift force is reduced considerably. Since the resistive force on the foil is now much greater than the lifting force, there will be little or no force exerted upward. In the case of an airplane wing, this angle of attack would produce a “stall” and the pull of gravity would cause the plane to fall downward.

### **THE ROLES OF LIFT AND DRAG FORCES IN SWIMMING PROPULSION:**

As mentioned earlier, Brown and Counsilman (1971 ) were the first persons to propose that lift forces were responsible for swimming propulsion. They suggested that swimmers propelled themselves in a manner similar to the one illustrated in Figure 9.

The underneath view of the butterfly swimmer in Figure 9 shows him sculling his hands back and in under his body at mid-stroke. The diagonal direction of the scull produces drag forces opposite the direction his hands are moving. That is, the drag forces are being exerted out and forward.

Notice that the swimmer’s hands are inclined inward. This combination of hand direction and inclination, or angle of attack, supposedly created a Bernoulli effect where the relative flow of water over the top of the hands was

faster than underneath. Consequently, lift forces were believed to be produced at right angles to the drag forces.

Notice, also, that, in Figure 9, the swimmer's hands are not moving directly sideward like the foils in Figure 8. Consequently, the lift forces are not being exerted forward. You might wonder how can swimmers be propelled forward when the lift force is not exerted in a forward direction. It can happen because both the lift and drag forces have forward components which combine to create a component of force called a **resultant**. In swimming, we refer to this resultant force as the **propulsive force**.

Assuming for now, that the lift theory of propulsion is valid, propulsive forces could be labeled as either drag-dominated or lift-dominated but rarely, if ever, can they be said to be exclusively one or the other. Propulsion of the type illustrated in Figure 9 would be thought of as lift-dominated because the lift vector is longer than the drag vector. Consequently, lift forces contribute more to the propulsive force. By the same token, if the drag vector were longer than the lift vector, propulsion would be characterized as drag dominated because drag force was the largest contributor to the propulsive force.

If drag forces predominated in swimming propulsion we would expect to see swimmers moving their limbs in nearly straight backward directions with angles of attack that were nearly perpendicular to the direction their limbs were moving. By doing so, large drag forces will be directed nearly forward where they can make their greatest contributions to propulsion. Sculling would simply not work. Sculling diagonally across the water with the limbs pitched perpendicular to the direction they are moving, would create large

drag forces in sideward, upward and downward directions. These drag forces would push their bodies sideward, upward or downward instead of forward.

On the other hand, if lift forces dominated swimming propulsion, we would expect to see swimmers making diagonal sculling motions. We would also expect to see their limbs pitched at small, but optimum, angles of attack to the directions they are moving. That is precisely what the best swimmers are doing when their stroke patterns are depicted relative to a fixed point in the pool as was illustrated in Figure 2.

With that rather lengthy introduction, I would like to move on to the primary reason for this paper. That is, to critique the various theories of swimming propulsion that are presently being debated in the literature. First, I'll discuss the validity of two theories of lift propulsion that involve the Bernoulli effect. The logic of drag dominated propulsion of Newtonian origin will be discussed in the next section. Then, I will try to synthesize pertinent information from each of the previous sections into a comprehensible theory of swimming propulsion. The final part of the paper will deal with suggestions for resolving the controversy concerning these divergent theories of swimming propulsion.

## **IS SWIMMING PROPULSION CAUSED BY LIFT FORCES?**

Brown and Counsilman's (1971), in addition to finding that swimmers were sculling their hands through the water, also suggested that they were shaping and angling their hands and feet like foils to produce lift propulsion.

Schleihauf (1979) was primarily responsible for testing their theories. He measured the magnitude of drag and, what he believed to be, lift forces exerted on a plaster model of a swimmer's hand while suspended in a water channel. The water was pushed past the plaster hand at velocities similar to those used in swimming. The hand was oriented so water flowed over it in eight directions that simulated the relative flow of water over the hand during actual swimming. These directions, known as **sweepback angles**, were:

1. Directly over the hand from the thumb toward the little finger side.
2. Diagonally over the hand from a direction near the fingertips on the thumb side toward the outside heel of the hand on the little finger side.
3. Directly over the hand from the fingertips to the wrist.
4. Diagonally over the hand from the fingertips on the little finger side toward the outside heel of the hand on the thumb side.
5. Directly over the hand from the little finger to the thumb side.
6. Diagonally over the hand from the heel on the little finger side toward the fingertips on the thumb side.
7. Directly over the hand from the wrist to the fingertips.
8. Diagonally over the hand from the heel on the thumb side to the fingertips on the little finger side.

The effect on the lift forces produced by angles of attack ranging from 0 to 90 degrees were measured for each of these sweepback angles with strain gauges.

Schleihauf published coefficients of lift in graph form for all of these conditions. His results are reproduced in Figure 10. They show that coefficients of lift were greatest for angles of attack between 30 and 50 degrees at nearly all sweepback angles. The one exception occurred when the water was flowing directly over the hand from the thumb toward the little

finger side. The highest lift coefficient occurred at an angle of attack of 15 degrees in this case.

Schleihaut's graphs for lift coefficients were very similar in shape to those produced for airfoils except that the coefficients were approximately 20% lower in value for the plaster hand. His conclusion was that swimmers' hands could act like a hydrofoil and produce lift forces in the water.

Schleihaut combined these data on lift and drag coefficients into formulas for calculating the propulsive forces produced by swimmers' hands and forearms. Other elements of the formula included, directions of limb movement, hand size, and angle of attack. These formulas have been used extensively, particularly in the U.S., to estimate the propulsive characteristics of world-class swimmers.

Two recent studies have cast some doubt on the validity of these formulas and the dominance of lift in swimming propulsion. Holt and Holt, (in a study that was reported by Rushall et al. in 1994), tested for the existence of lift forces about the hands. They attached tin-like baffles across the backs of swimmers' hands so the boundary layer would separate and no significant amount of lift could be produced. Swimming speed was reduced by only a small amount, approximately 2%, when the subjects swam with these baffles attached. Based on this result, Holt and Hold concluded that lift forces played a minor role in swimming propulsion.

Ferrell (1991) went much further in a recent study, concluding that lift of Bernoullian origin does not contribute to swimming propulsion in any way. He placed "tufts" (small plastic strips approximately 1 inch in length) on

plaster models of swimmer's left hands. The drawings in Figure 11 represents a plaster hand with tufts attached. The tufts were affixed to the backs of the plaster hands at only one end so that the other end would wave free in the water. The hands were then drawn through water at speeds of 0.3 to 3.0 m/s and angles of attack ranging from 0 to 40 degrees. The movement of the plaster hands was recorded on videotape each time they were drawn through the water. Forty-five different trials were conducted in all.

The idea behind this procedure was to use the tufts as a vehicle for visualizing the pattern of water flow around the plaster hand. If water flow was laminar, the tufts would all be waving across the hand in the same direction, that is, opposite the direction the plaster hand was moving. The tufts would be waving in random directions if the flow was turbulent over the top of the plaster hand.

Ferrell concluded that there was not one single incidence where there was not significant turbulence as water flowed over the top of the plaster hand. This was true even when the hand was moving slowly at an angle of attack of zero degrees. Turbulence was exhibited by 95 to 100 percent of the tufts when the hand was moving rapidly at an angle of attack of 30 degrees. Most researchers have reported hand angles of attack between 30 and 60 degrees when athletes are swimming at race speeds (Hinrichs, 1986, Luedtke, 1986, Maglischo et al., 1986, Schleihau, Gray & DeRose, 1983, Schleihau et al., 1984 and 1988, Thayer, et al., 1986). The drawing in Figure 11 shows an artist's reproduction of video pictures of the movement of tufts about a plaster hand pitched at a 30 degree angle of attack.

Ferrell concluded that the amounts of turbulence exhibited by the tufts indicated a separation of the boundary layer over the top of the hand which, in turn, negated any possibility that lift forces could be produced at the angles of attack and hand velocities used by competitive swimmers.

Although these results seem to cast serious doubt on the existence of lift during swimming propulsion, they are by no means conclusive. The tufts method can be misleading. This is because boundary layers often become turbulent and unstable without separating. This phenomenon is illustrated by the photos in Figure 12. The photo in Figure A shows a turbulent boundary layer that is still intact over the top of a sphere.

In Figure 12B the boundary layer has detached over the top of the sphere and then re-attached a short distance later. The area of swirling molecules at the point of detachment is known as a **bubble vortex**. Pressure is decreased over the top of the hand by the formation of bubble vortices which actually contributes to the production of lift forces. They increase the distance that adjacent streams of water molecules must travel to get from the leading to trailing edges. Therefore, the water molecules in those adjacent streams are caused to flow even faster which results in a further increase in the pressure differential between the underneath and top sides of the hand.

Consequently, bubble vortices and the turbulence accompanying them can actually contribute to increasing lift force so long as there is not complete separation of the boundary layer over the top of the hand. Therefore, the existence of turbulence, even significant turbulence, over the top of the hand does not necessarily indicate that a separation of the boundary layer has occurred. As a consequence, tufts could easily appear to be turbulent when

blown about by a turbulent boundary layer and bubble vortices. However, rather than signaling the absence of lift forces, this turbulence could actually provide evidence of the production of even greater lift forces. In actuality, if the boundary layer was separated the tufts in the separated region would probably exhibit no turbulence at all. (See Figure 12 )

With all due respect to his efforts, Ferrell's study has not provided conclusive proof of the absence of lift forces in swimming. Neither can the study by Holt and Holt be taken as conclusive proof that lift plays little, if any, part in swimming propulsion. Holt and Holt assumed that the placement of baffles on the top of their hand model would cause separation of the boundary layer. Whether they actually did so remains to be proven. Baffles may have simply disturbed the water flow over the top of the hand without separating it. In which case, the swimmer would have to use more force and/or faster limb velocities to achieve the same magnitude of lift forces. Nevertheless, the large amount of turbulence exhibited about the plaster hand in Ferrell's study, and minimal decrease in swimming speed that occurred when Holt and Holt used baffles must be considered an indictment against lift forces in swimming that deserves further study.

Another argument that has been made against the existence of lift forces concerns the "stall" angle of airfoils. It has been shown repeatedly that the boundary layer will become detached from the top of an airfoil when its angle of attack exceeds 14 degrees (Brancazio, 1984). Why then should we expect the boundary layer around swimmers' hands to remain attached at angles of attack of 30 to 50 degrees and more? There are actually two reasons why swimmers may be able to produce a significant amount of lift force at these angles of attack.

First, aerodynamics experts are becoming increasingly aware that the creation and augmentation of unsteady flow over the top of an airfoil actually produces an increase in lift forces when the wing is pitched at angles of attack in excess of 14 degrees and traveling at slow speeds. This is because of the the formation of bubble vortices. We know that swimmers' limbs are moving through the water much more slowly than hydrofoils and that the water flow around their limbs is always unsteady in nature. Therefore, it might be expected that they would use larger angles of attack.

Swimmers may also be manipulating their hand-foils to produce something akin to a **slotted-wing effect** that is common in aerodynamic flight. Wings are designed so that one portion can be partially separated from another to gain altitude at slower speeds during take-off and prevent a sudden loss of altitude at slower speeds when landing.

The slotted-wing effect is illustrated in Figure 13. It operates as follows. When one portion of the wing is separated from another by a short distance, the air underneath will be pushed up and backward through the small slots and over top edge of the wing. The air gains velocity as it travels through the slots causing a further acceleration of air over the top of the wing. This will, in turn, reduce the pressure over the topside, the pressure differential between the bottom and top surfaces will become greater, and the lift force will be increased. Birds also use a slotted-wing mechanism when they are soaring.

Swimmers may be utilizing a slotted-wing effect when they separate their thumbs from the rest of their hands, or raise one or more fingers higher than the others, as they sometimes do during their underwater armstrokes. A slotted-wing effect is illustrated for a hand in Figure 13. The spaces (slots)

between the thumb and hand and between the fingers may allow the relative flow of water passing under the leading edge of the hand to be accelerated up and over the upperside. This will maintain or increase the pressure differential between top and bottom so that a significant amount of lift force can be exerted in spite of the fact that the angle of attack of the hand is nearly 40 degrees.

## **WHAT PART DOES VORTEX FORMATION PLAY IN SWIMMING PROPULSION?**

It should be apparent by now that the existence of laminar flow over the tops of swimmers' limbs is not essential to the production of lift forces. Cecil Colwin (1984) was the first person to draw our attention to the fact that the flow around swimmers' hands was unsteady. He pointed out that swimmers' limbs travel in a rotational manner where their velocity and angles of attack are constantly changing. This makes it doubtful that steady flow can be maintained. He described the role of vortex formation and shedding in maintaining a Bernoulli effect when the water flow is unsteady.

A vortex is an ever-widening circular motion of water. You can see a vortex at the rear of the foil in Figure 12b. Vortices are created when any sudden change in direction, angle of attack, and/or velocity of a limb disturbs the water around it. This causes the water to be set in motion and leads to the formation of vortices.

The formation of vortices is illustrated with an airfoil in Figure 14. The process begins with the formation of a starting vortex. Changes in motion cause eddies to be shed as the water passes over the trailing edges of the airfoil. The water molecules in those eddies tend to roll up toward the area of lower pressure above the airfoil setting the circular movement of a starting vortex in motion. According to Newton's action-reaction law, a vortex moving in one direction will create a counter vortex of equal magnitude swirling in the opposite direction. The whirling motion of fluids within the starting and counter-vortices will increase in magnitude until the water flowing underneath and the water flowing over the top join smoothly at the rear edge of the foil.

The creation of countervortex acts as a so-called **bound vortex**. Its effect on the production of lift forces is so significant that a bound vortex is also known as a "lifting vortex" (Prandtl & Tietjens, 1934). A bound vortex is not a physical reality but it affects the magnitude of pressure differentials between the under and upper sides of objects as though it were. The water is not actually circulating around the foil. Nevertheless, the force of the countervortex above the foil acts in the same direction as the flow over the top and, in so doing, increases its relative speed. At the same time, the force of the countervortex underneath is exerted opposite the relative direction of water flow, slowing its velocity. This increases the pressure differential between the underside and top (-) of the foil that is needed for the production of lift forces.

Colwin's notion of vortex formation adds credence to the lift theory because it explains how the Bernoulli effect could operate when the water flow around swimmers' limbs is unsteady. Nevertheless, complete detachment of the boundary layer would nullify the formation of a bound vortex and eliminate the production of lift forces. As was the case with foil-type propulsion in conditions of steady flow, the boundary layer must remain attached in order

for the effect of a bound vortex to take place. Consequently, if the boundary layer separates as Ferrell suggests, lift forces, even those due to vortex formation, could not contribute to swimming propulsion.

## **IS SWIMMING PROPULSION DRAG-DOMINATED?**

In a recent article, Rushall and others (1994) presented a argument for drag force as the primary propulsive element in swimming. It should be noted that these authors did not deny the existence of lift propulsion. They simply made the case that drag forces play a greater role than lift forces in most swimming strokes.

The underneath stroke pattern of Pablo Morales in Figure 15 was used to support their thesis ( Rushall, et al., 1994). This pattern was drawn from videotape recordings of Morales during the finals of the 100 meters butterfly at the 1992 Olympic Games where he won the gold medal. The pattern does not exhibit the exaggerated “S” shape we have come to expect. Instead there is very little out and in motion in the first half of the underwater armstroke and a very long backward component that extends from just after his hands entered the water until just before they left it. The authors suggested that drag force would have to be the primary propulsive mechanism in such a pattern.

Another underneath stroke pattern for Pablo Morales is shown in Figure 16, which provides a somewhat different interpretation, however. It was drawn from video recordings made at the 1984 Olympic Training Camp while he was swimming at race speed in training.

You'll notice that there is considerably more sculling in the early portions of the armstroke, which were quite propulsive, as you can see from the forward velocity pattern at the bottom of the graph.

Why are there such marked differences in the two patterns? Perhaps they reflect differences between swimming in training and competition, or changes in stroke mechanics during the intervening 8 years or simply errors in the procedures for collecting and analyzing data from video tape. The point I am trying to make is that we should not draw conclusions from one pattern. A large number of such patterns need to be viewed before making a decision about the nature of propulsion. The stroke patterns of world-class butterfly swimmers that have been published by other researchers (Hinrichs, 1986) more closely resemble the one in Figure 16 than the pattern in Figure 15. Consequently, the pattern in Figure 15 may simply be that of an individual swimmer who uses a minimal amount of lateral motion in his stroke while the majority of world-class butterfly swimmers who have been studied use considerably more lateral movement in their stroke patterns.

Rushall and co-authors (1994) also showed a stroke pattern for Kieren Perkins which indicated considerable backward movement through the middle of his underwater armstroke where propulsion would have to be drag-dominated. An estimate of his propulsive force was calculated using Schleihau's formulas. It showed that this backward portion of his stroke was the most propulsive phase. That stroke pattern and propulsive force graph are reproduced in Figure 17.

Unfortunately, estimates of propulsive force such as these are generally imprecise (Brancazio, 1984). Accurate estimates of the forces acting on a foil are difficult to compute in wind and water channels and “would be nearly impossible to obtain for such irregular and flexible surfaces as the hands of swimmers in water” (Sprigings & Koehler, 1990). Consequently, judgments about propulsion based on estimates of propulsive force need to be supported by other data before they can be accepted with confidence. The most accurate method for estimating the propulsive effect of swimmers’ movements involves measuring the forward velocity of their centers of mass.

A center of mass graph for Perkins’s left armstroke has been adapted from Cappaert and Rushall (1993) and is shown in Figure 18. Please notice that his body is accelerating forward at a faster rate during the first half of his armstroke than during the second half. On the other hand, the propulsive force graph in Figure 17, shows the greatest force produced during the second half of his armstroke.

It is unfortunate that Perkins’s stroke pattern was not compared to the velocity pattern of his center of mass so that we would know if the movements of his hands were more lateral, vertical, or backward during the periods of greatest swimming acceleration. I have tried to make such a comparison by taking the stroke pattern from Figure 17 and applying it to the graph of forward velocity in Figure 18.

The first peak of propulsion appeared to take place when his hand was moving down and out, while the second and largest peak occurred when his hand was sculling either down, back and in, or back and in. Notice also, that

his forward propulsion tended to fall off during the time when his hand was moving almost directly backward.

Comparisons of stroke patterns, propulsive force graphs and center of mass plots for other swimmers in the publication by Cappaert and Rushall (1993) showed similar discrepancies between propulsive force graphs and forward acceleration patterns. Forward propulsion as measured by the forward movement of swimmers' centers of mass was generally greater during times when swimmers were sculling their hands through the water than when they were pushing them almost directly backward.

The large amounts of lateral and vertical stroking motions employed by most world-class swimmers belie the assumption that most swimming strokes are drag-dominated. In fairness, it must be said that Rushall and his co-workers never made that statement. Nevertheless, many persons have incorrectly interpreted their writing to mean just that.

The great majority of stroke patterns that can be found in the literature contain a preponderance of sculling movements. Typical stroke patterns are shown in Figure 19. The front view stroke patterns of freestyle and breaststroke in Figures 19 A and D show large lateral and vertical arm motions. The side view and underneath stroke patterns for backstroke and butterfly in Figures 19 B and C show only a small amount of backward movement and large amounts of vertical and lateral sculling.

Backward motion is even less evident in the kick patterns of swimmers. Most surprisingly, the side view kick pattern for the flutter kick in Figure 19E shows that swimmers' feet move directly down rather than back on the downbeat and up and forward on the upbeat. The underneath kick pattern for breaststroke in Figure 19F shows that the feet move out and in much more than backward.

Skilled swimmers seem to prefer sculling to paddling. Nevertheless, proponents of drag propulsion believe the role of sculling movements is to counteract rotational forces while the major propelling forces are produced by paddling movements. *Lateral and vertical sculling motions are simply too predominant in the stroke and kick patterns of swimmers for their propulsive effects to be denied. It does not seem logical that skilled swimmers would expend so much time and effort sculling during each stroke cycle when their stroke patterns could be executed in such a way as to allow more backward movements of their limbs where drag forces could be used to greater advantage.* After measuring the amount of backward movement in the strokes of highly-skilled and less-skilled competitive swimmers, Reischle (1979) concluded that highly-skilled swimmers moved their hands backward significantly less.

It is also not logical that most swimmers would require such a preponderance of sculling motions to counteract rotational forces. Schleihau and others (1988) reported that members of the 1984 U.S. Olympic swimming team used stroke patterns that were much more diagonal than would seem necessary for this purpose. In freestyle, backstroke and butterfly, their diagonal sculls were at angles between 40 and 70 degrees to the forward movement of their bodies (see Table 1). Breaststrokers showed the greatest diagonality in their armstrokes, pulling at angles of 70 to 90 degrees to their forward movement. An angle of 90

degrees would indicate movement that was directly up, down, or sideward. A straight backward push would be made at an angle of 0 degrees to the swimmers' forward directions. This means that swimmers were making rather large diagonal sculling motions with their hands. I am not disputing that drag propulsion plays a role in swimming propulsion. The issue at question is whether drag is the primary propulsive mechanism. I don't believe the authors have proven that contention.

Having made this statement, it may surprise you to learn that I am in agreement with Rushall and his team of researchers in their belief that drag forces play a significantly greater role in swimming propulsion than most proponents of lift propulsion suggest. I am not in agreement, however, that the most effective propulsive phases of swimmers' armstrokes occur when they are pushing their limbs almost horizontally backward.

Even Schleihau, who is thought of by many as a proponent of lift propulsion, did not believe lift was the dominant force in swimming. In a study where members of the 1984 U.S. Olympic swimming team served as subjects, Schleihau and his co-workers (1988) reported that lift and drag forces played approximately equal roles in propulsion in three of the four competitive strokes. The exception was breaststroke where lift seemed to predominate. These authors results are shown in Table 2.

It is possible, however, that Schleihau may have exaggerated the role of lift when constructing his formulas for estimating propulsive force. There is some recent research, (Cappaert, 1992), which suggests that drag forces exceed those of lift during swimming. This would mean that drag was the dominant propulsive force in all strokes, perhaps, even breaststroke.

Cappaert performed direct measurements of lift and drag forces on plaster models of hands. The plaster hands were suspended in the swimming flume at Colorado Springs and water was pushed past them from the little finger side to the thumb side, (sweepback angle of 180 degrees) at various angles of attack from 0 to 90 degrees. Drag forces predominated over lift forces at all angles of attack studied. Coefficients of drag were 3 to 5 times greater than those of lift at all water speeds and at angles of attack between 10 and 50 degrees. Cappaert's results are reproduced in the upper bar graph in Figure 20.

In Figure 20, I have compared Cappaert's results to the coefficients of lift and drag measured by Schleihau (1979) at the same sweepback angle and angles of attack. Schleihau's coefficients are displayed in the bottom graph of Figure 20. I should mention that the hands were of different sizes and the velocities of water flow were different in the studies of Schleihau and Cappaert. Therefore, a direct comparison cannot be made between the actual coefficients of lift and drag computed by these two researchers. However, a comparison of the relative magnitudes of lift and drag at angles of attack between 10 and 80 degrees show that Schleihau's data identified lift as playing a much larger role relative to drag than did the data of Cappaert. In fact, lift coefficients exceeded those of drag at angles of attack between 20 and 40 degrees in Schleihau's study. On the other hand, Cappaert calculated drag coefficients that were 3 to 6 times greater than those of lift at these same angles of attack.

Although unrelated to this paper, another interesting finding of Cappaert's study was that the forearm played a significant role in swimming propulsion. The addition of forces produced by a forearm model to those of

the hand model was reported to increase drag by 22.8% at the fastest water speed. It increased lift by 42.5%. if these observations are accurate, it would mean that the forearm could contribute nearly 50% to the propulsive force produced by swimmers' armstrokes.

## **NEWTON OR BERNOULLI?**

In this section I will try to synthesize the information that has been presented thus far into a theory of swimming propulsion that may answer some of the questions that have been raised concerning the relative roles of lift and drag in swimming propulsion. Those of you who are looking for simple answers to these question will not find them in this paper.

It seems very likely that both lift and drag forces are contributing to propulsion. The critical issue that needs to be resolved before this question can be answered definitively concerns whether the boundary layer is separated over the backs of swimmers' limbs. If it is, then lift forces would not be playing a role in propulsion. If it is not, then swimmers may be producing lift forces in ways that are only now beginning to be understood. They may intuitively be using mechanisms such as the production and shedding of vortices and slotted-wing effects to increase lift forces. In addition, they may be using pulse-like sweeps at rather large angles of attack to encourage unsteady water flow over the backs of their limbs as a further mechanism for increasing lift.

I believe future research will show that swimmers are indeed using lift forces for propulsion. This does not mean, however, that lift is the predominant propulsive force. As indicated by Cappaert (1992), drag forces are probably larger in all phases of all swimming strokes, with the possible exception of breaststroke. Consequently, the principles of Bernoulli, Newton, and others are being used interactively by swimmers during the execution of their strokes.

The subject that needs to be addressed concerns whether swimmers are more efficient when they use large diagonal sculling motions as opposed to movements which are largely backward pushes. I believe sculling is the more effective method in most phases of the four competitive strokes. Those phases where pushing backward may be more effective will be addressed later in this paper. For now let me describe how I believe swimmers are using the principles of propeller propulsion to scull effectively.

## **SCULLING AND PROPELLER PROPULSION.**

Propeller propulsion is illustrated in Figure 21. A propeller is an inclined foil that rotates at right angles about a central axis or hub. A typical propeller such as found on an outboard motor or common house fan has blades that are cambered like airfoils and then given a twist from the distal to proximal edge, (the edge closest to the axis of rotation). This gives the blades a small angle of attack relative to their direction of rotation. In the case of an outboard motor, the water is forced back from the leading to the trailing edge of each blade as it whirls sideward through the water. The backward movement of the water produces a counterforce that propels the boat forward which is a Newtonian effect. At the same time, the change in

direction and momentum of the water as it passes under the blade increases pressure on that surface contributing to an increase in the pressure differential between the bottom (+) and top (-) of the blade. This increases the lift, which, of course, is a Bernoullian effect.

I believe swimmers use their limbs like propeller blades as they scull them diagonally through the water. Assuming for the moment that the boundary layer does not separate over the tops of their limbs, swimmers could be displacing water backward under their limbs allowing them to produce large lift forces despite the fact that they are using rough, irregular surfaces that only slightly resemble foils. In addition, they change directions periodically to enhance the shedding and formation of vortices that can increase the lift forces produced by their limbs.

Several authors have suggested that propeller-type propulsion is not possible in swimming because the limbs cannot rotate 360 degrees (Colwin, 1992, Rushall, et al, 1994). On a typical threeblade motor, that water which slips sideward around the first blade is caught by the next blade and accelerated backward. This process is repeated by the third blade and then again by the first blade and so on, so that very little water is lost in a sideward direction. Obviously, swimmers, using only one "blade" would not be capable of the same efficiency because much of the water they displace would eventually move sideward causing a large "drag penalty" for a relatively small amount of propulsion. That is, the drag forces produced will always be greater than the propulsive forces. In other words, swimmers would waste most of their effort producing large diagonal components of force to achieve a smaller forward component.

Nevertheless, given the “crudeness” of their foils, this may be the price swimmers must pay in order to swim as efficiently as they can. There are examples in nature of propeller-like propulsion with single blades. Fish swim by using their tails like propellers.

Fish use their tails to press sideways or vertically against the water at angles of attack that causes the water to move backward from the leading to the trailing edge of their tails. Since fish cannot move their tails in continuous circles, they quickly change the direction and angle of attack of their tails at the end of one stroke to accelerate water backward with a sweep in the opposite direction.

The principle is that of a propeller. Fish are performing oscillating movements with their tails at angles which are diagonal to the direction they (the fish) are traveling.

Swimmers may perform a similar type of propeller propulsion with sculling movements. An example of how they might do this is

illustrated with an underneath view of a freestyle swimmer in Figure 22. In Figure 22A the swimmer is completing an insweep. His hand and arm scull diagonally in and back at an angle of approximately 60 degrees to his forward direction. His palm and forearm are pitched in at an angle of attack of approximately 40 degrees. After the downsweep and catch, the change of direction to inward may cause the shedding of vortices and a lowering of the pressure above the hand. In addition, the inward pitch of the swimmer's hand-propeller causes water to be displaced backward for a short distance as the hand (and arm) pass through it from its leading edge, which is the

thumb-side of the hand, toward its trailing edge, the little finger side. The magnitude of the backward displacement of water is indicated by the black area under the large arrow.

The relative movement of this particular segment of water will change from sideward and backward to up and sideward once the swimmer's hand passes through it. However, its direction and momentum have been changed to backward for the short time the hand passed through. Therefore, the water will exert a counterforce of equal magnitude in the opposite direction that should help propel the swimmer forward. This counterforce, the shedding of vortices and formation of new vortices contribute to the pressure differential between the palm side of the hand where the pressure is greater and the knuckle-side where it is lower so that lift is increased. Thus, both the principles of Newton and Bernoulli are probably at work.

The inward sweep continues until his hand is approaching or passing the mid-line of his body at which time its gradual rotation inward has caused the angle of attack to approach the perpendicular. At that point, he smoothly reverses the direction and sweeps his hand and arm out, back, (and up) until it approaches the surface of the water. This phase of the underwater armstroke, the upsweep, is illustrated in Figure 22B.

The sudden change of direction, once again, causes the shedding of old vortices and the formation of new ones. When he changes the direction of his hand and arm to out and back during the upsweep, the swimmer will also reverse the angle of attack of his palm so that it is pitched out. In this case, the little finger-side of his palm will become the leading edge and the thumb-side the trailing edge of his hand-propeller. This combination of

direction and angle of attack will also cause a particular segment of water to be displaced backward from leading to trailing edges when his hand passes through it. The relative flow of water under his palm will be opposite that of Figure 22A, but the result will be the same. The backward displacement of water will produce a counterforce that will aid in propelling the swimmer forward by increasing lift forces, both through the action of displacing water backward and the formation of new vortices.

I am suggesting that swimmers propel themselves forward through the use of oscillating, diagonal (sculling) motions. These sculling motions are three-dimensional, combining lateral, vertical, *and backward* movements where the limbs rotate gradually in the direction they are moving. That rotation continues until the limbs approach a perpendicular angle of attack where the backward displacement of water would be all but eliminated and the swimmers would be propelled more sideward, upward or downward than forward. At that point, they will smoothly reverse the direction of their limbs and move on to another phase of the underwater armstroke.

It is conceivable that lift might be produced by moving the limbs directly to the side, down or up at small angles of attack. However, given the structural limitations of swimmers, it may not be possible to do so without utilizing larger angles of attack and incorporating some backward motion. The angles of attack swimmers use during these sculling movements may need to be greater than 14 degrees in order to displace water backward sufficiently to produce a large forward counterforce. At the same time, they must not be so great that they increase the sideward or vertical counterforces (the drag forces) to the point that a major sideward, or vertical thrust is given to their bodies.

An effective angle of attack for this purpose would obviously be somewhere above 30 degrees but less than 60 degrees. This is exactly the range of angles that have reported for world-class swimmers in the various phases of their underwater armstrokes.

While the previous discussion provides a strong argument for the existence of lift forces in swimming *only* if the boundary layer is not separated over the tops of their limbs. I believe it is safe to assume that separation does not occur with skilled swimmers. Otherwise, they would simply push the water back with their palms using only small amounts of sculling to change directions when necessary during the stroke cycle. Stroke patterns show that skilled swimmers use large sculling motions while center of mass velocity graphs indicate that they propel themselves very effectively with these movements. In many cases, more effectively than when they are pushing almost directly backward. This provides empirical evidence that they prefer sculling to paddling. Without some lift being produced, the drag penalty incurred by sculling would be so great as to make this method less efficient than paddling backward.

The reason for preferring sculling may be to increase stroke length and decrease energy output. The frequent changes of direction accompanied by the cyclic slowing and acceleration of limb velocities that occur with sculling motions allow the periodic shedding and formation of vortices. This, in turn, should increase the amount of lift forces, and thus, propulsive forces, produced over the course of the entire underwater armstroke. As a result, swimmers may be able to attain the same forward velocities with slower turnover rates and less effort.

Given that sculling may be more effective than paddling, swimmers must deal with the large lateral and vertical drag forces they produce. They may counteract these in the following ways. In strokes like butterfly and breaststroke, the tendency for sideward components of force produced by one arm to push the body out of lateral alignment will be cancelled by sideward forces produced by the other arm. In backstroke and freestyle, lateral kicks are probably used to cancel the effect of sideward counterforces produced by the arms. In butterfly, backstroke and freestyle, kicking up and down may play a role in cancelling vertical forces that the arms have produced. Breaststroke is unique in that vertical components of force produced by the arms may be used to lower the hips in preparation for the leg recovery. In a like manner, the downward component of force produced by the legs as they execute their propulsive phases may help return the hips to a horizontal position

## **PADDLING MOTIONS: WHEN DO SWIMMERS USE THEM**

What has just been written should not be taken to mean that swimmers, even world-class athletes, never use their hands like paddles. They do at certain points in every stroke and some swimmers use paddle propulsion to a greater extent than others. There is also a phase of the butterfly armstroke where pushing the hands backward may be preferable to sculling.

Swimmers seem to use drag propulsion when their limbs are changing directions during the transitions between the various phases of their underwater armstrokes. Examples of these transition points in each of the four strokes can be seen in the stroke patterns illustrated in Figure 19.

Swimmers generally push their limbs backwards and pitch their hands perpendicular to the direction they are moving after the catch and before their hand(s) sweep in under their bodies in all strokes.

Freestyle swimmers will also push their hands back and out, but mostly back from the time they start the upsweep until their hands are passing out from underneath their bodies.

Butterfly swimmers will push their arms back even more than freestylers during their upsweeps. They probably do this because they cannot scull out like freestyle swimmers during this phase. Since butterflyers are moving their arms simultaneously, they must remain flat during the upsweep of their armstrokes while freestylers can roll on their sides. This prevents butterfly swimmers from bringing their arms under their bodies as much, which, in turn, limits the amount of subsequent outward sculling they can do.

Backstroke swimmers will push their hands almost directly backward during a portion of the second downsweep, from the time they complete their first upsweep until their hand is passing their waist.

## **SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH**

The arguments for and against the various theories of propulsion are summarized in Table 3. How can we make sense of the contradictory research findings and opinions with regard to these mechanisms for swimming propulsion? On the one hand, we see stroke patterns and center of mass velocity patterns which demonstrate (1) a preponderance of lateral and vertical sculling motions during each stroke cycle, and (2) a considerable amount of forward acceleration accompanying these sculling motions. These data certainly suggest that, in addition to drag, there are other forces making a large contribution to swimming propulsion. Lift force seems to be the logical alternative.

On the other hand, swimmers' limbs are not designed to be very effective foils and drag forces do seem to predominate in their underwater stroking patterns. Perhaps swimmers are not capable of producing significant amounts of lift?

The following pieces of research are needed to determine if lift is involved in swimming propulsion.

1. Studies should be designed which will prove or disprove the existence of significant lift forces around swimmers' limbs. These studies should include valid methods for determining, (A) whether the boundary layer has separated over the top of swimmers' hands when they are actually swimming, and (B) the extent to which lift, drag, and propulsive forces are produced by real or simulated swimming movements.

The cheapest method for determining this would be to make a hand model which would allow small amounts of dye to be injected on to the surface of the hand periodically while it is being towed through the water. If the dye remains undisturbed in a particular area, then a separation of the boundary layer has taken place in that area.

A more expensive but also more accurate method would be to use “hot wire anemometers”. These are small wire filaments that can be, first, heated, then cooled by the water flowing over them. They could be mounted in a glove that swimmers wear and recordings could be transmitted to a computer by means of a battery pack. If the wires failed to cool in certain areas of the swimmer’s hand, then the boundary layer would have separated. Once such a glove is developed, it could also be used to measure pressure differentials during various types of stroking movements.

1. A second and even less expensive method of study would be to compare three-dimensional stroke patterns with graphs of the forward velocities of swimmers’ centers of mass. This would allow us to make judgments as to the relative contributions of sculling and paddle-like limb movements to forward propulsion.

Attempts to resolve this controversy of lift vs. drag propulsion will probably not lead to any significant changes in the stroke mechanics of our greatest athletes. They are, in most cases, instinctively applying the proper principles of propulsion with little or no academic knowledge to guide them. Nevertheless, resolving this issue has important implications for swimmer and coach alike.

It will lead to a more accurate understanding of the way in which swimming propulsion occurs and that will provide at least four valuable outcomes:

1. The teaching of stroke mechanics should become more effective because those mechanics will be taught from the correct perspective.
2. Fewer swimmers may have their strokes damaged by attempts at correction which are made from the wrong perspective.
3. Innovative and effective stroke techniques, i.e. the “wave breaststroke”, may be developed more frequently.
4. Coaches will become better at evaluating the potential effectiveness of suggested innovations in technique if they know the physical laws that govern swimming propulsion.

## **WHAT DO WE TEACH SWIMMERS IN THE MEANTIME?**

The various theories of swimming propulsion I have presented may leave you wondering how to teach the competitive strokes. Certainly, acceptance of one theory over the others may require some modifications in your teaching. Nevertheless, it should comfort you to know that you will not be far off should you choose the wrong theory. That is because sculling is the central propulsive mechanism regardless of the theory you select.

Whether swimming propulsion is drag dominated or lift-dominated does not change the fact that the majority of world-class swimmers are using sculling movements to propel themselves forward. Their underwater armstrokes and kicks appear to be combinations of lateral, vertical, and backward movements whose relative magnitudes may differ from swimmer to swimmer and are different according to the phase of the stroke they are in. Regardless of these small differences, the general patterns are similar from swimmer to swimmer. Consequently, we should study the stroke patterns

and angles of attack used by great swimmers and teach our athletes to use sculling motions that are similar to theirs.

Since no two persons swim alike, there will be times when we have to exercise our judgment about the extent to which the limbs should be moved and pitched in various directions. In those cases, rely on the stroke patterns which seem to be most common for guidance, or seek solutions through trial and error.