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Swimming Skill: A Review of Basic Theory

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Introduction

Over the past two decades, research in swimming biomechanics has produced a major reassessment of the basic theories surrounding swimming skill. This paper reviews research findings concerning the general theory of swimming propulsion. Further, the specific techniques employed by skilled swimmers in all four strokes are summarized. Finally, propulsive efficiency is discussed from a theoretical viewpoint in order to clarify the foundations of aquatic skill.

The discussion of swimming skill is presented from three levels of inquiry:

1. From the *kinematic level*, the fundamental patterns of motion utilized by skilled competitors is defined. Further, the basic principles of fluid mechanics are combined with data on stroke kinematics to provide a theoretical explanation of the propulsive mechanisms used in swimming. The Bernoulli principle theory of propulsion (that diagonal sculling motions provide the basis of efficient hand motions in swimming; Counsilman, 1969) is presented along with the early literature in this area. We will see that the Bernoulli principle theory of propulsion has the universal support of the scientific community. In contrast, the previously accepted push back-action reaction theory (that straight back pushing motions are used by good swimmers, Hedges, 1933; Silvia, 1970; Collis and Kirchhoff, 1974) is rejected on the basis of cinematographic evidence.

2. The original Bernoulli's principle theory on swimming propulsion has been extended through evidence collected at the *kinetic level* of analysis. At this level, estimates of the propulsive forces and joint torques employed by skilled swimmers are reviewed, and a refined description of the end product of aquatic skill is defined. Studies of outstanding swimmers help define the optimal interaction between the human organism and the aquatic environment. Our discussion includes the consideration that an impulse of hand force delivered within a critical range of motion is a fundamental characteristic of aquatic skill. In contrast, the view that efficient propulsion follows from a uniform production of force is rejected.

3. From a *theoretical level*, a discussion of the interdependence of biomechanical and physiological theories helps to solidify understanding of the techniques observed in skilled swimmers. Basic theory allows us to understand *why* skilled swimmers choose to use the techniques discussed at the kinetic level of analysis.

Analysis from the Kinematic Level

The Bernoulli Principle Theory

Counsilman (1969, 1971), and Brown and Counsilman, (1970), presented the first arguments which acknowledged the importance of lift force in swimming. It was stated that propeller like sculling hand motions were used by skilled swimmers instead of the previously supposed push back-paddling hand motions. The contrasting features of the Bernoulli principle of Propulsion and the action reaction viewpoint are illustrated in Figure 1.

In the action reaction theory a straight back pulling pattern is purported to provide optimal swimming efficiency. The hand is assumed to be held at right angles to its line of motion and drag forces are seen as the source of swimming propulsion. A canoe paddle is used as an example of a drag force producing implement. In contrast, the Bernoulli principle theory of propulsion states that curvilinear pulling patterns are made with respect to the water, acute hand angles are made between the hand plane and its pulling pattern, and lift forces play an important role in the production of propulsive force. A propellar blade is used as an example of a lift force producing implement.

Counsilman utilized light trace photography of swimming pulling patterns to support his theoretical viewpoint. Curvilinear patterns, similar to that of Figure 2 were presented to illustrate that many swimming hand motions exit the water in front of their point of entry. Note that a static camera position is used in the collection of the illustrated pulling pattern data. By holding the camera still, the motion of the swimmer's hand with respect to the water (and thus the propulsive action of the hand on the water) is isolated by the recorded pulling pattern data.

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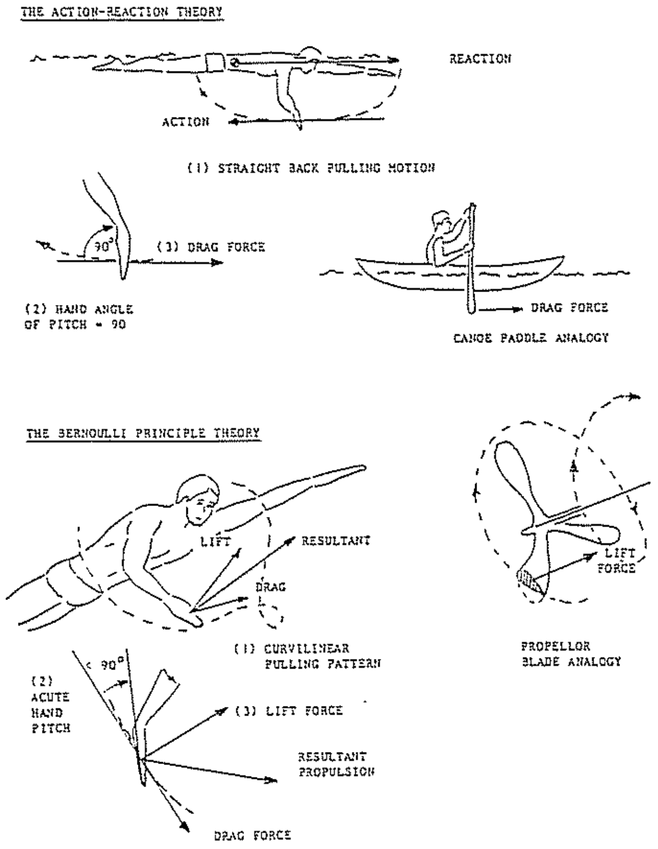


Figure 1. Action reaction vs. Bernoulli principle theories of propulsion.

The Bernoulli principle theory proposed that lift forces are produced by the swimmer's hands, feet and forearms. The mechanism responsible for the production of lift force is illustrated in Figure 3. Note that the lift force vector is directed at right angles to the line of motion of the propelling surface in each example. Thus, with an airfoil, lift forces are generally directed upwards; with a propeller, lift is aimed primarily forwards; and with curvilinear hand pulling patterns, the direction of lift forces change constantly, but is at right angles to the pulling pattern at any instant in time. Drag forces are also produced by wings, propellers and hands. The line of action of drag forces is opposite to the instantaneous line of motion of the propelling surface (Schleihauf, 1974).

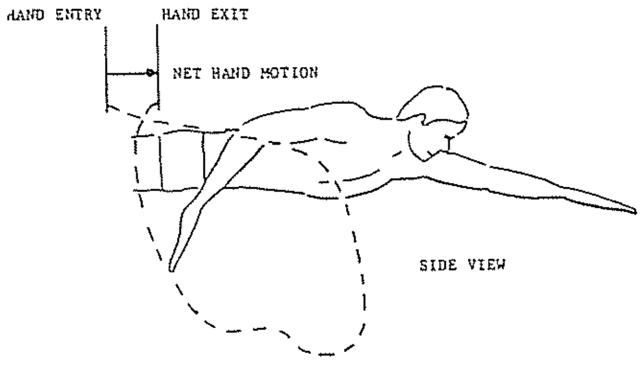


Figure 2. Freestyle pulling patterns.

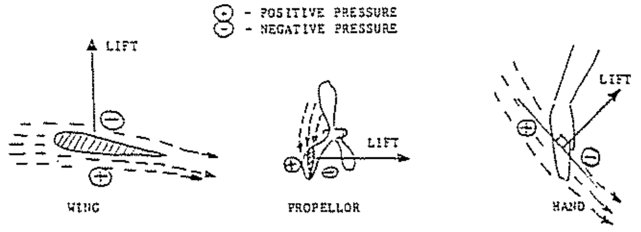


Figure 3. Lift force production. (+) indicates a high pressure region. (–) indicates a low pressure (partial vacuum) region. The lift force vector is produced as a result of the pressure differential and is aimed at right angles to the line of motion of each propelling member.

Hand Propulsion

Subsequent to Counsilman's 1969 article, numerous papers were published in support of the Bernoulli principle theory. Hay, 1973; Rackham, 1975; Barthels, 1981, 1979; Persyn, 1978; Ungerects, 1979; and Reichle, 1979 presented empirical information clarifying the analogy between skilled pulling motions and propeller like sculling motions. Quantitative cinematographic evidence was presented by Schleihauf, 1974 and Barthels and Adrian, 1975. Barthels and Adrian found that a parallel relationship existed between sculling hand motions and body acceleration in butterfly swimmers. Schleihauf found that a highly skilled freestyler utilized his most rapid hand actions in the side to side and up and down dimensions of motion. Further, it was shown that the combination of lift and drag forces acting on the hand may be expected to vary with hand pitch as shown in Figure 4.

If the hand moves through the water with a very small angle of pitch (about 15 degrees - Figure 4a) a small drag force component and moderate lift force component are created. If the hand employs a 35-45 degree angle of pitch, both the lift and drag force components produced are large (Figure 4b). Finally, if the hand uses a large angle of pitch (nearly 90 degrees - Figure 4c) a large drag force is created and almost no lift force is produced.

A typical swimming motion and hand pitch angle is shown in Figure 5. Notice that the 35 - 45 degree angle between the swimmer's hand and its line of motion creates

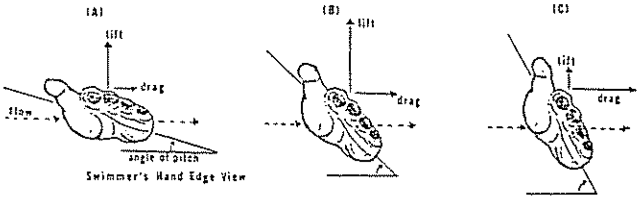


Figure 4. Lift drag interaction for three angles of hand pitch.

lift and drag force components which are approximately equal in size. Note that the hand propulsion force vectors shown in Figure 5 are identical to those of Figure 4b, with the exception that the hand line of motion of the freestyler is oriented along a diagonal line. As a result, the drag force acts opposite to the hand line of motion (upward and to the right on the page), and the lift force acts at right angles to the hand line of action (upward and to the left on the page). Because of the diagonal line of pull chosen by the swimmer, the hand resultant propulsive force (the net effect of both the lift and drag force components taken together) is aimed nearly straight forwards.

In effect, a swimmer can insure that hand propulsive forces are aimed forwards (and not wasted to the side or in up/down directions) by selecting an optimal hand pitch angle. For a pulling motion which progresses through the water along a 45 degree angle with respect to the forward direction (Figure 5) a 35-45 degree angle of pitch produces optimal results. For a pulling motion which is more sideways (as in the inward scull motion in breaststroke) a larger lift drag ratio is required to "aim" the hand forces forward. Thus, in breaststroke, smaller hand pitch angles (15 - 35 degrees) may be expected to yield propulsive forces which are aimed nearly straight forward.

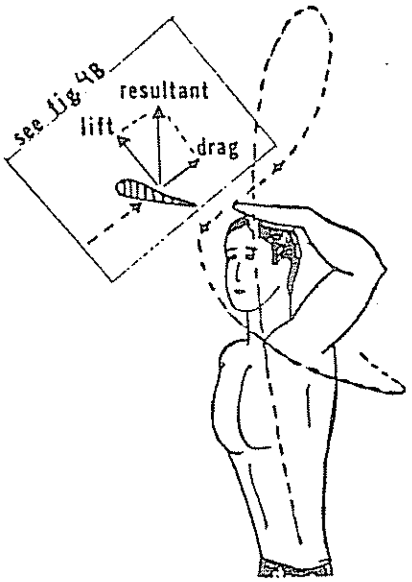
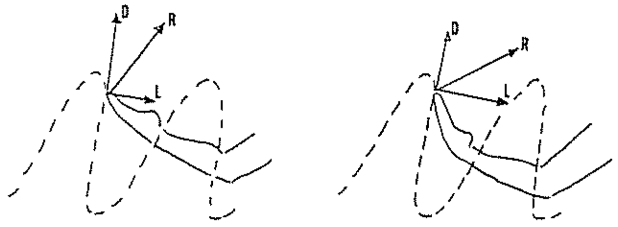


Figure 5. Forward propulsion through lift drag interaction.

Foot Propulsion

The Bernoulli principle theory may be applied to kicking propulsive actions as well as those of the hand. Studies of flutter kick movements have been shown to produce the saw-tooth pattern illustrated in Figure 6 (Hoecke and Gruendler (1975), Counsilman (1977) and Reichle (1982)).



A. POOR ANKLE FLEXIBILITY B. GOOD ANKLE FLEXIBILITY

Figure 6. Flutter kick propulsion.

An analogy may be drawn between kicking patterns and propellar blade motions. On a down thrust the foot may be expected to produce the propulsive force components shown. Propeller blades are designed to change their orientation with respect to the propeller axis in accordance with varying speeds of progression of the boat. This change in propeller orientation allows for the maintenance of acute angles of pitch at any boat speed. In the case of a human foot, the "variable pitch feature" is limited by the degree of plantar flexion ankle flexibility. With greater ankle flexibility, more acute pitch angles are possible and less force is lost in the up-down dimension (Figure 6b). In effect, the flexible ankle allows for an acute angle of pitch and a high lift drag ratio (see Figure 4a.) With a relatively large lift force component, the net propulsion produced by the kick is aimed more forwards.

Analysis from the Kinetic Level

In the previous section, the characteristics of skilled movement patterns and a theoretical explanation of the propulsive forces generated in swimming were discussed. In the following paragraphs experimental evidence is presented which substantiates the Bernoulli principle theory of propulsion.

At the onset, it must be noted that while the majority of the scientific community accepted Counsilman's theory, there were those who preferred to maintain the push back-action reaction viewpoint. For example, Holt, (1976), published an empirical argument which denounced the possibility that lift force could be created by the human hand.

In support of the Bernoulli principle theory, research from the fluid mechanics laboratory (Schleihauf, 1977) presented experimental evidence in support of the importance of lift force in propulsion. Models of human hands were placed in the open water channel and propulsive characteristics were defined across a wide range of hand orientations with respect to the water flow. The force producing qualities of the hand were shown to be virtually identical to those of a low aspect ratio (short stubby) airfoil. Subsequent research, Wood (1979), Remmonds and Bartlett (1981), and Nomura (personal correspondence) produced results similar to Schleihauf (1977, 1979).

The experimental evidence on hand propulsive force potentials provided for both the confirmation of the Bernoulli principle as well as a mechanism for the substantial extension of the original theory. Through the combination of fluid laboratory data and a film analysis procedure, an objective evaluation of the biomechanical aspects of swimming skill may be defined.

The Hydrodynamic Analysis Procedure

The motion of a hand through water is governed by the same physical principles which have been established in airfoil/propeller blade research. The degree of skill of a competitive swimmer depends upon his or her mastery (at a subconscious level) of skills which conform to these physical principles. Conversely, the accurate analysis of a skilled swimmer's hand motion may only be accomplished in conjunction with a complete understanding of hydrodynamic theory.

The quantification of the force producing characteristics of the hand may be expressed in terms of coefficient of lift (Cl) and coefficient of drag (Cd) versus angle of pitch curves. Figures 7 and 8 show representative Cl and Cd values determined in Schleihauf (1979), for a hand held flat, with fingers together and thumb fully abducted. The data in the curves confirm the supposition that hydrodynamic theory applies equally well to wing, propellor and hand motions. Figure 7 indicates that the lift force produced by a hand held at a small angle of pitch is also small. As the hand pitch increases, lift force builds to a maximal value around 40-45 degrees. Thereafter lift force diminishes with increasing angles of pitch. Figure 8 indicates that drag force increases continuously with increasing angle of pitch. Given the information contained in these curves, estimates of the forces produced by any type of hand motion in water can be computed.

Note that each Cl and Cd value depends upon two variables: 1) The hand angle of pitch (AP); measured as the angle between the hand plane and its line of motion. And, 2) the hand sweepback angle (SB); which defines the leading edge of the hand as shown in Figure 9a. Figure 9b shows the difference between a hand orientation of AP = 35, SB = 0 and AP = 35, SB = 90 (degrees).

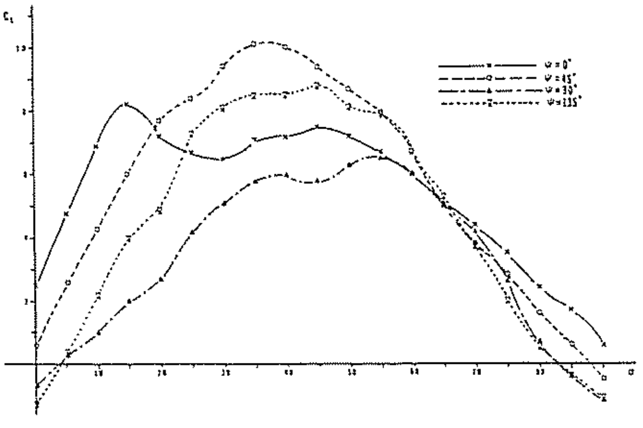


Figure 7. Coefficient of lift vs. angle of pitch curves.

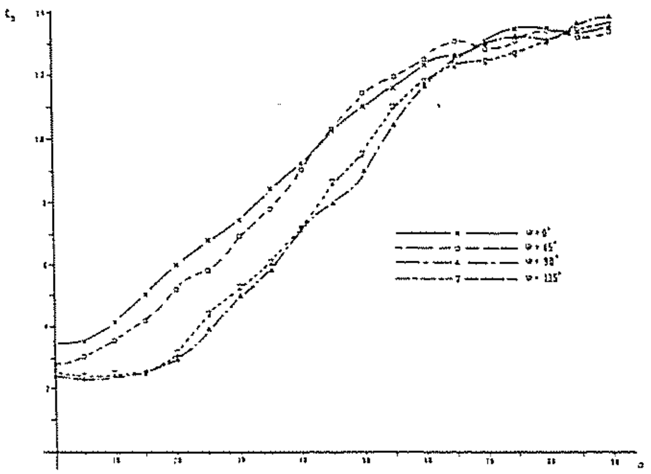


Figure 8. Coefficient of drag vs. angle of pitch curves.

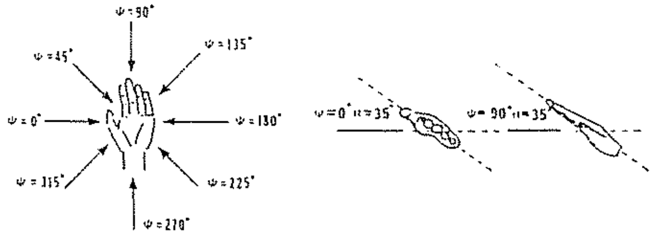


Figure 9. A) Sweepback angle measurement convention. B) Two flow condition examples.

Given the quantitative information on hand Cl and Cd values, it is possible to estimate hand propulsive force based upon cinematographic information. Four lighted landmarks on the hand may be digitized from two film views to supply the necessary information on hand orientation and hand speed to allow solution of Equations (1) and (2):

$$L = \tfrac{1}{2}\, Ro\, V^2\, Cl\, S \quad (1)$$

$$D = \tfrac{1}{2}\, Ro\, V^2\, Cd\, S \quad (2)$$

Where:

L = magnitude of hand lift force
D = magnitude of drag force
Ro = density of water
V = hand speed
Cl = coefficient of lift
Cd = coefficient of drag
S = hand plane area

Further, the direction of the hand propulsive force vector may also be determined from three dimensional coordinate data on the hand. A complete description of the data reduction procedure is given in Schleihauf, et al., (1982).

Validation Experiments

In order to determine an estimate of the degree of accuracy to be expected with the hydrodynamic analysis procedure, three experimental conditions were studied (Schleihauf, 1977, 1979). In the experiments a swimmer was asked to balance a known load while performing a vertical sculling, tethered breaststroke pull, or tethered freestyle pulling task (Figure 10). Three dimensional film data was collected on a stroke cycle in which the resisting load was being evenly balanced.

The film data was then reduced and estimates of hand and forearm force production were made at each instant in the arm pull. The computed force output — which is based upon the fluid laboratory data and film analysis procedure — was then compared to the known load the swimmer was balancing. The results showed that in three separate stroking motions, the estimated propulsive force data was within 5% of the expected values.

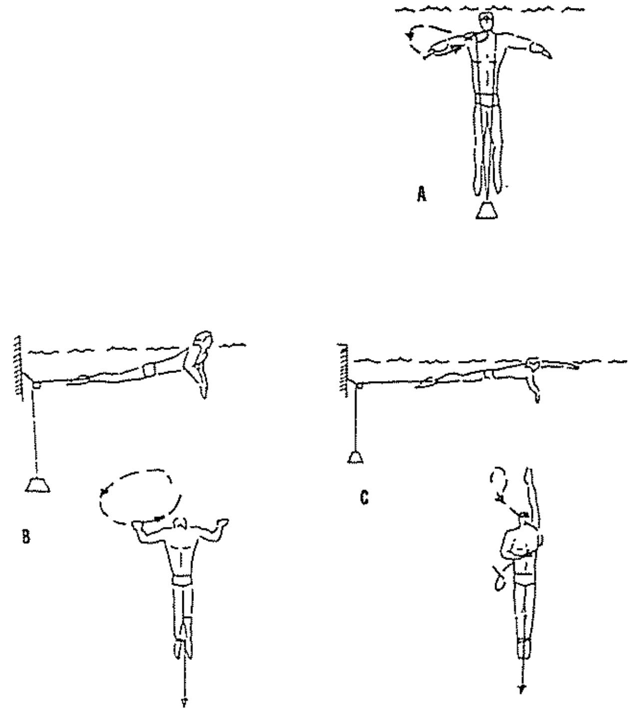


Figure 10. Validation experiments. A) Vertical sculling. B) Tethered breaststroke. C) Tethered freestyle.

Advantages of the Hydrodynamic Analysis Method

A primary advantage of the hydrodynamic analysis procedure is that it may be applied to any hand and arm motion in water. Through simple film records we are able to quantify not only the kinematics but also the kinematics of human motion. Such a complete analysis potential from film alone is not easily accomplished in other areas of biomechanics. Typically, force plate or force/pressure transducer data must be combined with filmed records to yield similar results. It is also interesting to note that while direct measurement techniques are generally more accurate than film techniques, this is not the case in swimming. Pressure transducers have been used to measure the hydrodynamic pressures which are produced at the palm of the hand during free swimming. In early studies, (Van Manen & Rijken, 1975) the transducers were so large and bulky that the lift drag force producing characteristics of the hand were undoubtedly altered. In subsequent studies, (Dupuis, et al., 1979), the transducers were much smaller, but the pressure recordings included both the hydrostatic pressures—due to the depth of the hand underwater—as well as the hydrodynamic pressures which resulted from propulsive hand motions. In recent work (Svec, 1982), a pressure transducer paddle has been developed which corrects for the hydrostatic pressure component, and measures propulsive pressures only.

Even with the Svec pressure transducer, it must be noted that the direct measurement of palm pressures yields a rough estimate of hand propulsive force at best. Figure 11 shows the pressure distributions which exist on wings at two different angles of pitch. Note that the pressure component which exists at the mid-point of the underside of the wing is a poor estimator of the overall force acting on the wing. Further, even if the pressure measured at a point on the hand palm were representative of hand force, the information would be meaningless without knowledge of the force direction. Figure 12 shows two swimming motions which produce identical force magnitudes. The pressure recordings would theoretically show equal measures of palmar pressure for Figure 12a and 12b, even though the stroke of Figure 12a provides six times more effective propulsion. As a result, pressure transducer studies of free swimming would need to be supplemented by film analysis in order to yield data meaningful to the coach or athlete.

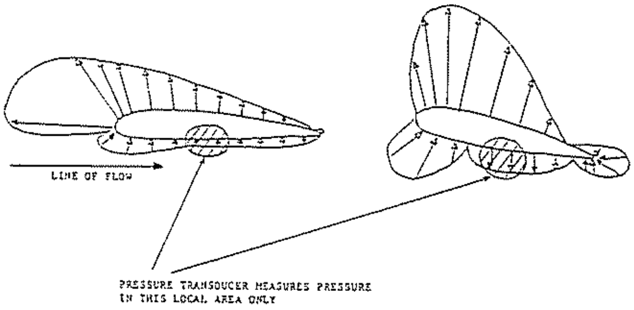


Figure 11. Wing pressure distributions.

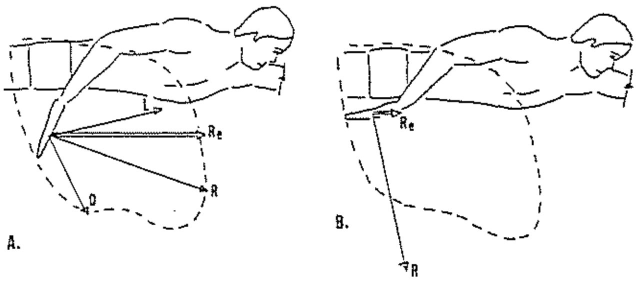


Figure 12. A comparison of hand force direction. Lift (L), drag (D), hand resultant force (R) and hand effective resultant force (Re) are shown. Re represents the portion of the resultant force vector which is aimed forward.

Applications of the Hydrodynamic Analysis Method

The hydrodynamic analysis procedure has been used in a variety of case studies in an effort to define the essential ingredients of aquatic skill. In the following paragraphs, the characteristic pulling patterns, hand force distributions and joint torque distributions which are employed among skilled swimming competitors are defined.

Pulling Patterns of Highly Skilled Swimmers

The sculling motions which are characteristic of the four competitive strokes are illustrated in Figure 13. (Note: For simplicity, in each view the lift-drag plane is shown in the plane of the paper. In most instances, the three dimensional hand force vector includes components into or out of the paper.)

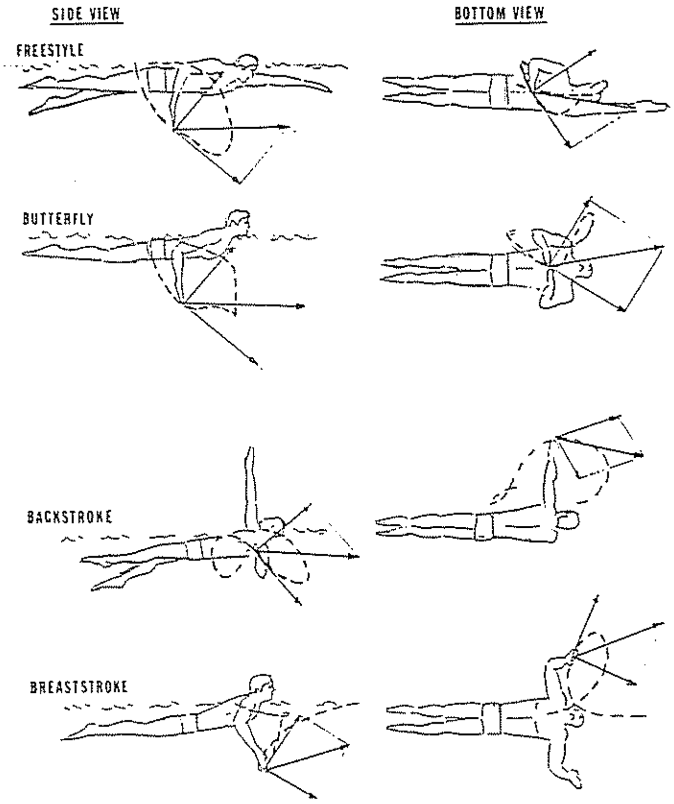


Figure 13. Key propulsive forces and pulling pattern orientations.

The above figure shows that zig-zag curvilinear pulling patterns are used in each of the four competitive strokes. In each stroke, diagonal pulling motions make use of the principle of lift-drag interaction to create efficient propulsion.

Freestyle, backstroke, and butterfly involve pulling patterns which form an angle of approximately 50 to 70 with the forward dimension. These diagonal lines of pull are helpful in creating propulsive forces which are aimed primarily forwards. In the case of breaststroke, a pattern orientation of about 75 to 95 with the body's line of progression is created on the inward scull action of the stroke. As a result, in breaststroke, the propulsive force is angled to the side and upward as well as forward.

It should be noted also that, within a given competitive stroke, a range of optimal stroking styles may be expected across a sampling of skilled swimmers. Depending upon the individual's strengths, flexibilities and training backgrounds, "ideal" patterns vary with individual swimmers. (See Schleihauf, 1977 for a more extensive review of swimming styles in all four strokes.)

Propulsive Force Distributions

An analysis of the propulsive forces created within a stroke cycle indicates that an impulsive force distribution is characteristic of skilled stroke technique. A typical effective propulsive force curve for each of the competitive strokes is shown in Figure 14 a-d. The critical range of the pulling pattern which is associated with the propulsive peaks is cross hatched in both the hand resultant (R) force curve data and the pulling pattern for each stroke.

The data presented in Figure 14 is taken from Schleihauf (1981). Counsilman and Wasilak (1980) on the basis of hand speed data, have also theorized that optimal propulsion follows from impulsive force distributions. They state: "The power pulses from the arm stroke are applied in surges and the maximum force generated by the hand peaks near the end of the arm stroke." Similarly Svec (1982), has presented pressure transducer data which suggest that impulses of hand force are applied in swimming.

Joint Torque Computation

The joint torques (net muscular actions) which occur at the swimmer's wrist, elbow, and shoulder may be determined through established biomechanical procedures (Andrews, 1974), once the arm propulsive forces and kinematics are known. The details of the swimming computational procedure may be found in Schleihauf, et al., (1982).

The joint torque curves for a skilled freestyler are shown in Figure 15. The largest torques of good swimmers appear to occur at the shoulder joint, where the net muscular actions are about twice as forceful as these at the elbow.

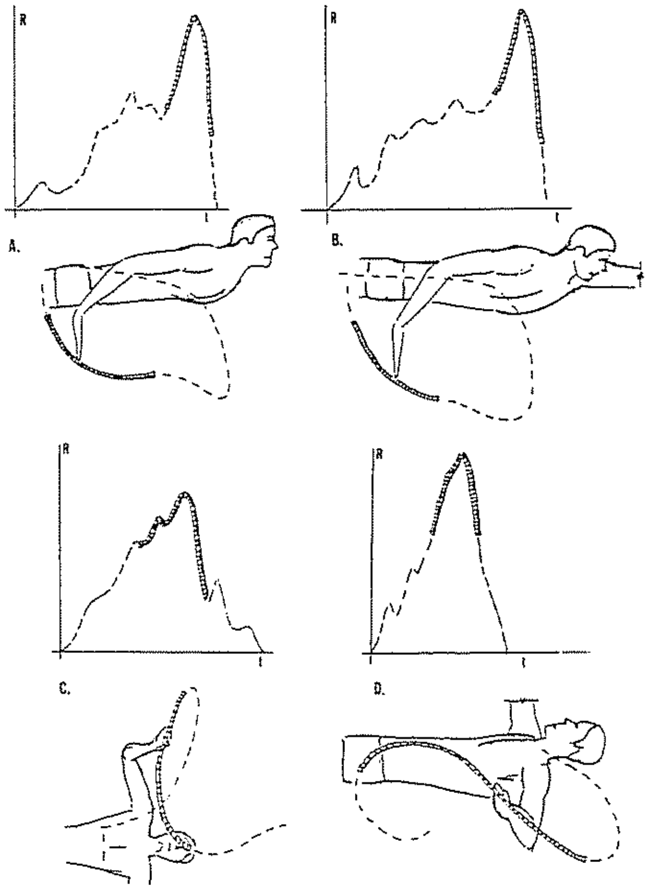


Figure 14. Hand resultant force (R) versus time (t) curves shown with pulling patterns for each stroke. A. Butterfly. B. Freestyle. C. Breaststroke. D. Backstroke. The critical range of motion is cross hatched in both the pulling pattern and the hand force curve.

The trends in the joint torque curves echo the impulsive hand force distributions we have seen above.

Clarys (1981) presented EMG data in support of our observations on joint torque. The shoulder muscular actions of skilled swimmers were shown to be more intensive than those of the elbow. With poor swimmers, the opposite situation was found; elbow muscular actions were more intensive than those at the shoulder.

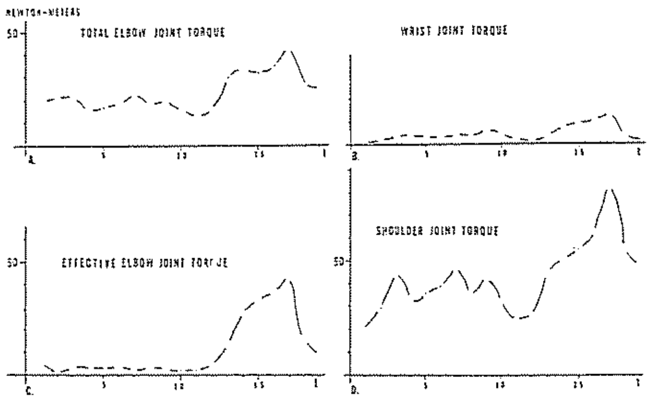


Figure 15. Freestyle arm joint torque magnitude versus time (t) curves. A. Total elbow joint torque. B. Wrist joint torque. C. Effective elbow joint torque (the elbow joint torque component acting parallel to the elbow joint axis). D. Shoulder joint torque.

The above discussion describes the ingredients of aquatic skill from a biomechanical viewpoint. Next, the propulsive efficiency of skilled aquatic motions is discussed.

Optimization of Propulsive Efficiency - Theoretical Viewpoints

Observations of the movement patterns and propulsive force output of skilled swimmers provides an external view of the ingredients of aquatic skill. In order to achieve an understanding of the internal processes which produce propulsive force, our next step is to consider the muscular contraction circumstances of skilled swimming movements.

The Efficiency of Sculling Movements

Schenau (1981) has made the important observation that swimming performance is limited by three factors:

1) The net propulsive force produced (as discussed above).
2) The active drag or the resistance created by the swimmer as he proresses through the water.
3) The propulsive efficiency created by the combination of the swimmer's muscular effort and the mechanics of his motion.

The third point above is frequently overlooked in the literature. While a swimmer's performance may seem to be a simple interaction of his propulsion and active drag, it is also important to note that a given net propulsive force output may be produced with a variety of physiological efficiencies.

For example, consider the motions shown in Figure 16a and b. In each of the illustrated motions, the hand speed in the water (and therefore, the approximate force potential) is identical. However, the movement speeds relative to the swimmer's body are not the same. In the push back motion, 4.71 meters per second (mps) relative to the body is required to produce 3.05 mps relative to the water. In the sculling motion, only 4.15 mps relative to the body is required to produce a 3.05 mps water speed. This information implies that sculling motions translate hand movement speeds to the water more efficiently than push back motions.

Figure 16c shows Perrine and Edgerton's (1978) in vivo force velocity relationship for human muscle (adapted from Hill's equation). The maximal force possible at a given speed of contraction is represented by the illustrated curve. Note that the maximal potential force of a slower contraction speed is higher than that of a fast contraction speed. Thus, the slower movement speed (4.15 mps) associated with the sculling motion above would involve a higher potential force production than the push back

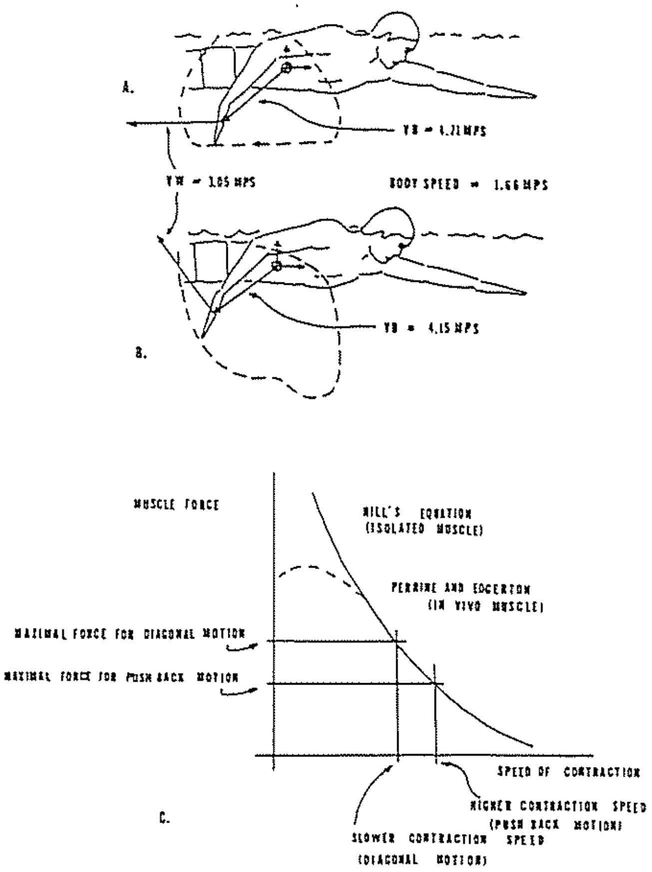


Figure 16. A. Hand speed measured relative to the water for a push back motion. B. Hand speed measured relative to the water and the body for a typical sculling motion. C. The relationship between muscle force and speed of contraction.

motion (4.71 mps). As a result, we see that sculling motions have a greater maximal propulsive force potential than push back motions.

Further, Figure 17 shows how a large lift force component can take maximal advantage of the muscle's force velocity characteristics. In the figure, a large shoulder joint torque component is required to balance the hand lift force. It is interesting to note that while this shoulder joint torque seemingly attempts to create a rotary motion about the long axis of the upper arm, there is actually minimal motion of the arm in this direction — the breaststroke inward scull action is primarily inwards. As a result, the shoulder joint torque is created with very slow muscular contraction speeds. Again, muscle force velocity relationships indicate that the force potential of these near isometric contractions is much higher than that of higher speed muscular contractions.

As a general rule, the slow contraction speed advantage such as that shown in Figure 17 occurs whenever the hand propulsive force includes a component which is parallel to the instantaneous axis of rotation of the joint. A review of hydrodynamic analysis data indicates that the contraction speed advantage occurs in varying degrees in sculling motions, but can not occur in push back motions.

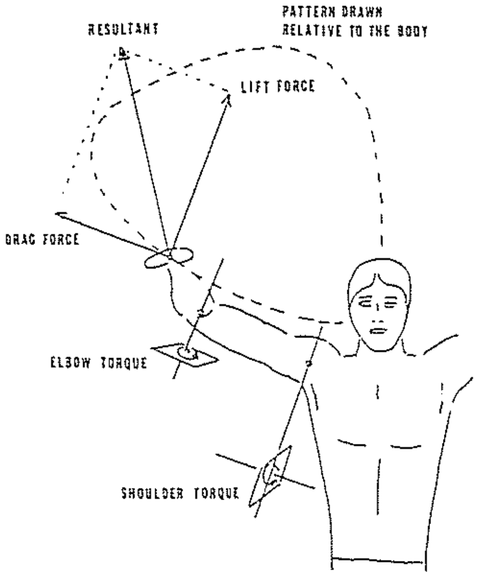


Figure 17. Breaststroke joint torques.

It should also be noted that in freestyle, curvilinear sculling motions tend to be combined with shoulder roll actions. The combination of body roll along with the upward swept finish of a freestyle stroke, allows the strength of the large muscle groups of the trunk to be transferred to the hand through the serape effect (Logan and McKinney, 1970).

Figure 18 shows that sculling finishing motions combine the strengths of the trunk muscles along with the shoulder and elbow joint muscle groups. In contrast, a straight back pulling motion — with no forceful upward swept movement component — would not take advantage of shoulder roll or the potentially powerful shoulder joint rotations.

Theoretical Support for Impulsive Force Distribution

The above discussions provide theoretical arguments which confirm the importance of zig-zag curvilinear sculling motions in swimming. In this section, the theoretical

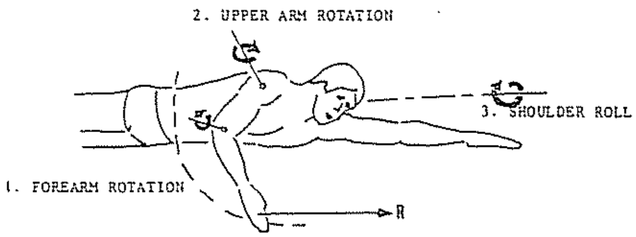


Figure 18. The serape effect and the freestyle arm stroke. The forearm rotation (1), upper arm rotation (2) and shoulder roll (3) combine to produce the hand resultant force (R).

issues which support the use of impulsive force distributions are discussed.

First, we should note that the importance of impulsive force distributions in swimming has only recently been realized. Prior to the Bernoulli principle theory, efficient propulsion was presumed to follow from a uniform square wave distribution of propulsive force.

The mechanical rationale for the efficiency of the square wave propulsive force distribution is given by the smooth running eight cylinder automobile engine. In a car, the uniform torque sent to the drive wheels was expected to minimize the inertial lags (acceleration/deceleration) of the system. The explosions which occur in an automobile engine may be carefully timed to produce a seemingly continuous flow of torque to the drive shaft. In the case of swimming, however, the mechanical analogy breaks down. The movements of a two arm stroke swimmer (or a two legged runner) can hardly be likened mechanically to the rolling of a wheel. While it is clear that the propulsion from a given arm stroke should flow continuously to the next, it is not clear that within a given stroke, a uniform force output is desirable. For example, studies of fish swimming (Wiehs, 1974) show that an overall optimal combination of mechanical and physiological efficiency results from burst swimming — where large impulses of power are followed by glide phases in the swimming movement. Similarly, in running, the horizontal ground reaction force component in no way approximates a uniform production of force. Finally, in human swimming, a pulse of propulsive force output, followed by a gliding phase is clearly evident in many stroking styles.

The zig-zag line of pull which is employed in sculling motions in itself necessitates the use of impulsive force distributions. Figure 19 shows that with each change in pulling direction, the hand speed must slow down, and force must necessarily diminish (Area A). In the middle of a diagonal motion the hand achieves peak speed, and peak force (Area B). Finally, at the end of the stroke a smooth transition to zero force occurs as the hand moves out of the water to begin the recovery. These biomechanical circumstances are responsible for the natural occurrence of a force pulse near the middle of a diagonal motion.

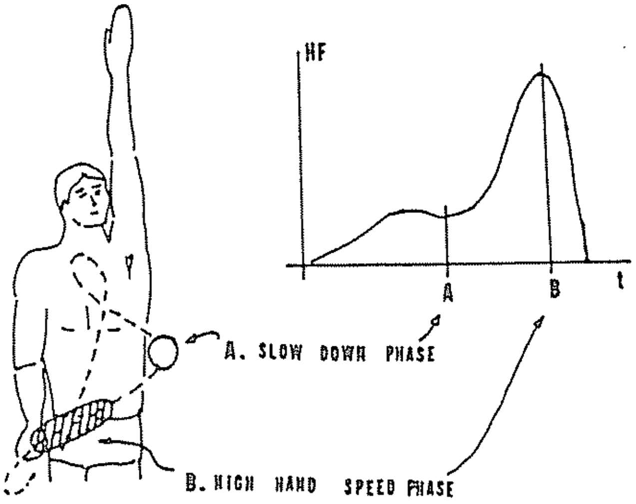


Figure 19. Diagonal pulling patterns and impulsive force distributions.

A pulse of force seems to be economical from the neurophysiological level as well. Perrine and Edgerton, 1978, found that on an isokinetic knee extension exercise, their subjects were able to reach higher instantaneous force levels if a ramp like build up of force was planned by the subject. Even though the contraction took less than 2 seconds, the impulsive "effort" distribution gave higher peak values than uniform "100%" efforts. Perrine and Edgerton attributed the success of the impulsive method to "neutral fatigue" which may be present in very short duration maximal intensity muscular effort.

Finally, our serape effect argument would seem to support the observation that some swimming motions create much larger pulses of force than others. For example, the finishing portion of a freestyle arm pull produces a force pulse which is much larger than the mid-stroke segment. It seems that the swimmer's can best "seize the moment of least resistance" (Bernstein, 1967) at the end of the stroke where the benefits of sculling actions, strong muscle groups, and the serape effect all combine.

Conclusions

In the foregoing discussions, the basic theory surrounding aquatic skill has been discussed from kinematic, kinetic and theoretical levels. The following list summarizes our main points:

1) Sculling hand actions are used by skilled swimmers in all four competitive strokes.
2) Diagonal pulling patterns allow straight forward propulsion through the combination of lift and drag force.
3) A pulse of propulsive force is created within an isolated pulling area in each stroke.
4) Within any sample of swimmers, there is a range of efficient propulsive styles, each suited to the individual attributes of a given swimmer.
5) The muscle force vs. contraction speed relationship seems to favor sideways and diagonal motions for optimal translation of a swimmer's hand speed to the water.
6) Curvilinear pulling patterns allow efficient energy expenditure through the use of large muscle group activity (the Serape effect) in the generation of a pulse of force.

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