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Editor's Preview

This issue starts with a Viewpoint Article by Rushall, et al that explores the debate over how forces are applied during swimming. The primary focus of the paper is on propulsive forces (specifically lift and drag) and the authors challenge the notion that most of swimming propulsion is lift-oriented. Although a contribution of lift is acknowledged by the authors, the major premise seems to be that the arm action in strokes other than breaststroke provides propulsion in a drag-dominated manner. Furthermore, the authors make the case for the forearm being more important in propulsion during freestyle swimming than was perhaps thought. Resistive forces are also discussed in this paper in relation to their possible contribution to performance. In our efforts to improve swimming performances, issues such as the one presented in this paper are fundamental to our strategies for teaching swimmers how to swim.

The next three papers in this issue are original investigations relating to blood lactate responses in long course versus short course pools (Lowenstein, et al), whether swimmers need supplemental carbohydrate during long practices (O'Sullivan, et al), and if maximum oxygen uptake and ventilatory threshold measured on dryland are reflective of physiological demands of middle-distance swimming (Swaine). The Lowenstein, et al paper describes a study in which blood lactate responses are shown to be higher in long course pools than in short course pools even when swimming at the same velocity. This has been approached by earlier studies but, unfortunately, the early studies failed to control for the added distance in 200 meters vs. 200 yards or failed to control for possible differences in velocity. These possible variables have been controlled in this paper. The authors propose that the reason for the higher blood lactate response in long course pools may be the greater number of turns in short course which may offer a slight degree of intermittent rest for the muscles primarily involved in the swim. Does the higher blood lactate response in long course pools imply that swimmers need more lactate tolerance training or more aerobic endurance training to reduce lactate accumulation when preparing to compete in long course pools?

The paper by O'Sullivan, et al examines whether carbohydrate feedings during a long training session can help prevent a decline in blood glucose concentration and improve performance at the end of the training session. There are numerous reports that for runners and cyclists performing long endurance exercise, carbohydrate feedings can be very effective in preventing a fall in blood glucose and improving performance. The great reliance of swimmers on interval training, however, may influence whether carbohydrate feedings would be as effective in swim training as they have been in running and cycling. This paper shows that for most of the swimmers used in this study, there seemed to be no need for the carbohydrate feedings. In individual cases, however, the carbohydrate feeding did prevent declining blood glucose and improved late-practice performance. Further research should try to determine the prevalence of declining blood glucose among swimmers and factors that may cause some swimmers to experience this.

The paper by Swaine describes a study in which dryland measures of maximum oxygen uptake and ventilatory threshold are correlated to performance of 400 m freestyle performance. In addition, indices of stroke rate, distance per stroke, body size, and stroke index are added to the analysis to assess the degree to which a combination of stroking, anatomical, and physiological variables can predict 400 m performance.

Stager and Lanting also offer another installment of their bibliography entitled, “In Print: Swimming 1989”. This bibliography lists published articles on swimming related topics for the year 1989. The bibliography is published periodically in the Journal of Swimming Research as a service to readers who may have an interest in searching the literature published during the targeted year.
KEITH SUTTON

Keith Sutton was selected as the ASCA Executive Director following Bob Owsley who retired in 1983. He served as Executive Director from January 1984 to August 1984 when he tragically passed away.

The JSR is a product of his desire to provide each segment of the ASCA membership with services appropriate to their interests.

He and his wife Mary did literally all of the initial work to bring this idea to fruition and following his death, Mary continued as editor of the JSR for the next seven years. In 1990 Mary was presented with the Robert Owsley award for special service to the ASCA for her devotion of this publication.

Keith would be proud of the direction that current editor Rick Sharp has provided for the Journal and all of American Swimming owes a debt of gratitude to Keith Sutton for insisting on a legitimate peer reviewed journal in which scientific studies may be tested and published.
A Re-evaluation of Forces in Swimming

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Abstract

The development of thinking and research over the past 25 years for understanding the basic properties of force production in swimming strokes is discussed. The limitations and deficiencies of Bernoulli's Principle for being the sole explanation for propulsive forces are presented. Bernoulli's Principle is simply too limited and inappropriate for accounting for observed and measured phenomena in competitive swimming strokes. Lift forces have been shown to be minor in the propulsive phases of the crawl, back, and butterfly strokes.

In breaststroke, both drag and lift forces are recorded in the inward and outward sculling phases of the stroke. However, drag forces are not in a facilitatory direction and so forward propulsion results from lift created by an exaggerated angle of attack (when compared to those exhibited in crawl, back, and butterfly strokes), and a large canceling of the effect of the mostly symmetrical drag forces. The dominance and importance of lift forces in breaststroke is not a justification for promoting Bernoulli's Principle as the foundational reason for propulsion.

Drag forces are dominant and in a facilitating direction during propulsion in crawl, back, and butterfly strokes. The extent of their importance is markedly more than lift force contributions.

Several practical considerations were drawn from the assertions made. They will require a change in the teaching/coaching emphasis of many practitioners who promote an exaggeration of the S-shaped pull, that is, they believe that large sideways movements are beneficial for propulsion. A greater emphasis should be placed on orienting swimmers to focus on the role of the forearm in propulsion, particularly at higher speeds.

Three forms of resistance were proposed for consideration. They have practical implications for coaches. Frictional drag can be reduced by shaving and wearing a suit with a fabric that has a low coefficient of resistance. Form drag can be minimized by maintaining streamlined positions during the entirety of all strokes. Wave drag can be minimized by removing any unnecessary vertical and all lateral and exaggerated movements. Attention to the details of drag reduction is most important when speed of swimming is emphasized.

The production of force is important. However, resistance increases at a much greater rate than changes in speed due to propulsive forces. Thus, it is advocated that swimming actions first should be oriented to minimizing resistance, and second, to developing propulsion as long as positions for minimal resistance are maintained.

A change in entrenched thinking with regard to propulsive and resistive forces is warranted. When that change is made and its importance introduced into coaching, the progression of swimmers' performances should improve.

Forces in Swimming—Current Status

The intention of this paper is to clarify the foundational principles involved in both propulsion and resistance in competitive swimming. Currently, there are controversial issues surrounding the bases of propulsive forces created in the four competitive strokes. Initial incomplete descriptions of those forces are still popular. The impact of types of resistance on swimming speed are not well understood. The clarification of these topics should produce better understandings and hopefully, more effective coaching.

This review does not dissect each competitive stroke
or explain techniques. It only covers the theoretical bases of force production and the nature of resistances. More detailed explanations of technique will have to remain for another forum.

An Historical Perspective

In the 1950s and '60s, James “Doc” Counselman and Charles “Red” Silvia applied principles of mechanics primarily to the propulsive forces of competitive swimming strokes. In the early years, descriptions of actions were related to what was observed in swimming actions by champion swimmers. Some credence was given to Newton’s Third Law of Motion, “To every action there is an equal and opposite reaction,” which accounted for drag forces, as being the theoretical basis for propulsive forces. However, in the late 1960s, Counselman proposed that propulsion was gained through “lift” rather than drag force. The basis of that force was Bernoulli’s Principle. At this time Silvia (22) continued to interpret forces in competitive swimming strokes as being derived from Newtonian Laws, that is, when force is applied backward, a swimmer will be propelled forward.

“Doc” Counselman was possibly the most profiled coach/scientist in swimming during the 1960s and '70s. His charismatic and personable nature, remarkable successes as a coach, and his logical academic exposition of swimming training and techniques created his reputation as a very credible source of information and knowledge. “Red” Silvia, equally impressive in personal and academic qualities, was not as high-profiled and so his “teachings” were not as universal as those of Counselman. Both men impacted swimming research, particularly through the pragmatic evaluation of the stroke patterns of champion swimmers. However, it cannot be denied that Counselman’s pronouncements were accepted faithfully as being true and accurate. Others also contributed to swimming knowledge at this time, but Silvia, and in particular Counselman, were the main theorists of the period.

Counselman’s effect on persons in swimming was remarkable. His popularity as a teacher at Indiana University meant that he was able to educate many receptive students about swimming mechanics. His very frequent world-wide clinics and his swimming camps added to his fame and profile. However, it is possibly his book “The Science of Swimming” (6), the most published and translated text on swimming, that established him as the “world-authority” on swimming.

In “The Science of Swimming”, Counselman described propulsive forces on the surface of the hand being created in a similar fashion to those on the surface of an oar—that is, a drag force is created as a direct application of Newton’s Third Law. The direct force was not reconciled with the curved paths of actions observed and reported in swimmers and frequently referred to as S-shaped or “inverted question mark” pulls. Resistance was described solely as a quadratic relationship to the speed of the swimmer (“The theoretical square law”).

However, in 1969, Counselman committed himself to a radical change in the theoretical basis of propulsive forces in swimming. He proposed Bernoulli’s Principle as the explanation of those forces. His followers were very quick to adopt this stance and conclude that “lift” forces were the major forces that produced propulsion in all competitive swimming strokes. For a brief time, “lift” was considered the only force for propulsion. However, as the limitations of sole lift explanations became apparent, “drag” forces (of Newtonian origin) crept back into the propulsion equation. Without any empirical evidence, but rather by intuitive analyses, “researchers” analyzed strokes of swimmers promoting lift forces as being the predominant propulsive force. For example, Schleidau (18, 19) attributed the primary value of drag forces as being “The drag component of the hand could neutralize eccentric kicking forces and the lift component could approach its maximum value.” Such a position was echoed by Barthels: “... proposed the ideal condition of maximizing the propulsive force and minimizing propulsive drag.” Many persons, particularly those outside of the USA, appeared to become enamored with the Bernoulli’s Principle explanation of propulsive forces and persist with it today (e.g., Swimming Coaching Accreditation Scheme, Australia). Counselman did modify his initial exclusivity of lift force being the only force in propulsion. Over time, he talked more of hand pitch (“angle of attack”) as a significant determinant for creating force but never really focused on drag force as a major determinant of propelling efficiency. He continued to emphasize a sideways orientation of stroke movements in the S-shaped or hourglass pull as facilitating lift and therefore, producing the forces to create speed in swimming.

As with any good science, attention often turns to the objective verification of theories that are postulated. Larry Holt and his students at Dalhousie University in Canada, initiated detailed evaluations of the forces created by the hand and forearm in strokes other than breaststroke. Direct measurements, believed to be the first conducted, showed that at only some stage of an arm pull is the swimmer propelled or accelerated by the arm action and that during the propulsive phase it is drag force that is the major contributor among the forces created. Holt’s work remained buried in relatively obscure scholastic books that were published some years after their completion (26, 27, 28, 29). The pioneering works of Holt and his students will be discussed in more detail below.

The popularity of Bernoulli’s Principle as being the
theoretical basis for swimming propulsion continued through the years. It was adopted by noted authorities such as Jim Hay (10) in biomechanics and Ernest Maglischo (16, 17) in swimming. The longevity of the blind acceptance of the "Bernoulli-Principle-explanation" for propulsion in swimming will remain a discussion topic in the history of sport science far into the future.

Very recently, the description of the arm actions of all swimming strokes has been advanced by the work of Jane Cappaert at US Swimming’s International Center for Aquatic Research (ICAR) in Colorado Springs. Objective analyses of the stroking patterns of gold medalists during finals races at the 1991 World Championship in Perth, Australia, and the 1992 Barcelona Olympic Games have been produced. The previous research weaknesses of describing what happens when elite swimmers perform in training swims and inferring those movement patterns to competitive performances plus restrictions to two-dimensional views of swimming, have been removed. The scientific value and accuracy of Cappaert’s work has been independently verified by personal visitations from, and assessments by, a number of scientists during the ICAR review in 1993. Cappaert has drawn attention to the production of both lift and drag forces in the development of propelling efficiency in all strokes. Only in breaststroke, do lift forces exceed the importance of drag forces during propulsion. Independent of Holt’s and Cappaert’s work, Springs and Koehler (23) at the University of Saskatchewan, questioned the appropriateness of trying to use Bernoulli’s Principle as the model to explain the lift phenomenon. They pointed out that both lift and drag can be better understood using Newton’s Second and Third Laws as the predictor model.

The consideration of what forces slow a swimmer’s forward movement has received less attention. It is very possible that minimizing the resistances created in movements could allow swimmers to improve in swimming speed. In 1933, Karpovich (13) described resistances of swimming as being skin friction, eddy resistance, and wave-making resistance. The details of that delineation have been lost over time. Most considerations of resistance have revolved around active and passive resistance (5). Sheehan and Laughrin (21) improved on the theoretical considerations of resistive forces involved in moving through a fluid medium by reviving and refining Karpovich’s categories. Their work allows a more detailed consideration of actions and their resistance effects in swimming strokes.

The actions, proposals, and researches indicated above, are considered to be “landmark” activities in the development of understanding forces in swimming. They will serve as the basis of describing the current status of the topic. It is recognized that others have contributed to the knowledge of swimming but it is not possible to produce a complete anthology of all authors’ works in this forum.

Propulsive Forces

Bernoulli’s Principle

Bernoulli’s Principle states that fluid pressure is reduced whenever the speed of flow is increased. The difference in pressure between two flows is described as dynamic lift. The most common application of Bernoulli’s Principle is to the shape of an asymmetrical airplane wing. A curved upper surface produces a faster flow of air than does a lower flat or concave surface, resulting in a pressure differential. Lift of this nature acts on the body in a direction perpendicular to the path of the object movement through a fluid.

Typical references to the appropriateness of this principle to swimming have appeared in the literature. Maglischo (16) accounted for lift as follows: “The amount of lift force is proportional to the difference in pressure between the two wing surfaces which is, in turn, dependent upon the shape of the wing surfaces and the forward speed of the airplane.”

Counselman (8:61) stated: “A wing provides aerodynamic lift through the camber (curvature) of its surfaces. Because the upper surface is more highly cambered than the lower surface, the air moving over the top surface is forced to move more quickly. This results in a lower pressure on the upper surface as compared with the lower surface and results in aerodynamic lift (Bernoulli’s Principle).”

These references are typical of the allegiance of most swimming “authorities” to the lift force derived from the principle. Such references are misleading (23).

The method of difference is often used as a logical procedure to justify the appropriateness of Bernoullian lift in swimming. What authors typically attempt to do is explain why drag cannot possibly be a “good” force for swimming. This is done by analogizing devices that are not particularly successful in propelling efficiency and showing their similarities to the actions of swimmers. By eliminating them as propulsive models and the drag component that was inefficient in each circumstance, it is deduced that Bernoullian lift must be the remaining force that is useful. There are three common analogies that continue to be reproduced in the literature (18).

1. Figure 1 illustrates a caterpillar paddle wheel that relies on pushing water directly backward to produce a reactive forward force. The problem with this wheel is that trailing blades in the water are subjected to turbulence created by the leading blade which in turn,
reduces their ability to create force. It is generally asserted in this argument that for a swimmer to push directly backward is inefficient because the hand will be working in “moving” water. Many people have accepted this argument as being correct. However, it has one flaw that is so simple that many overlook it. *A swimmer does not have many arms in the water at the same time.* Thus, the illustrated analogy is invalid. When a swimmer has one arm propelling backward it is in relatively undisturbed water and never gets into the problem of the trailing blades of the caterpillar wheel. This example is not a justification for avoiding the creation of drag forces to produce propulsion.

2. The second typical example is that of a circular multi-bladed paddle wheel that turns on an axis (see Figure 2). The problem with the paddle-wheel blades is that only at the bottom of the rotation is a force created directly backward causing maximum forward propulsion. A swimmer is shown once again with three arms in the water, each being straight. Apart from the incorrect analogy of the many arms, the second error is in the depth of the illustrated swimmer's pull. Swimmers are not restricted to arms that are locked straight. By manipulations of the angle of bend at the elbow, repositioning of the shoulder capsule, and rolling the body, it is possible to create a force in a primarily backward direction that will propel the swimmer forward. The analogy used in this example is invalid for swimming.
SUPPOSEDLY ROTATING ARM ACTION

Figure 3. The spinning-propeller analogy. The comparison with a swimmer is incorrect. A swimmer only completes half a stroke in the water and cannot rotate the arm in the shoulder joint in a spinning fashion. In this illustration, the swimmer and propeller are going in opposite directions. The inference of the need for circular and sideways movements in swimming strokes by using this analogy is illogical.

3. The third example is one of a propeller, using Bernoulli’s Principle, and a swimmer alongside with curved lines drawn to show a circular, spinning path of action (see Figure 3). Although it is assumed that this illustration was meant to convey the idea of how forward “lift” can be developed by a lateral movement, it runs the risk of misleading the reader. It is safe to say that a swimmer’s arm action in crawl stroke cannot possibly function in the rotational manner of a propeller and any analogy between a swimmer’s arm action and a propeller must be treated with skepticism. This analogy also is invalid for swimming.

These three examples are invalid and therefore, do not serve to eliminate the possibility that drag forces can be beneficial in swimming strokes.

It should be realized that the original promotion of Bernoulli’s Principle as the “reason” why swimmers move forward was conjecture. What is needed is verification that the propulsive forces of swimming are predominantly lift and that the hand and forearm from the radial and ulnar edges are lifting surfaces if the Bernoulli interpretation is to be supported.

If Bernoulli’s Principle was the appropriate model for explaining propulsion in swimming, the following would have to be true:

1. The forces that exist for propulsion are only lift forces. Bernoulli’s Principle only accounts for lift and cannot predict or explain drag. Since it has been shown that drag forces are important for propulsion (see discussion below), the principle is inappropriate.

2. The shapes of the hand and forearm need to be that of an asymmetrical wing. A cursory glance at both anatomical parts disputes this requirement. What is more restrictive is that in swimming an S-shaped stroke, on the out sweep the ulnar edge of the hand and forearm would have to be curved and bulky while the trailing radial edge would have to be tapered. The shape would then have to be reversed on the insweep, an anatomical impossibility. Therefore, the principle is inappropriate because the hand and forearm are not the required shapes to exploit its properties efficiently.

3. The Bernoulli model assumes, in its derivation, that energy in the fluid system is conserved. While this can be a reasonable working assumption for laminar flow conditions, the same assumption is certainly not tenable for the turbulent flow conditions which accompany competitive swimming strokes.

These three features indicate that Bernoulli’s principle is inappropriate as the model to explain propulsion in swimming. Evidence will be presented later that measures the amount of lift that occurs with the hand and forearm in strokes other than breaststroke.

Wood and Holt (29) measured the lift properties of plaster casts of four swimmers’ hands and forearms simulating positions in swimming the front crawl stroke in a wind tunnel. Three basic flow orientations were tested, the radial, ulnar, and distal borders. In all cases the shapes of the limb components were much better at creating drag forces than lift forces. The greatest lift occurred in the distal orientation, that is, when the flow moved from the finger tips up the arm, an action that is not associated with swimming propulsion. It was
demonstrated that the hand and forearm are not effective "lifting surfaces" and are not applicable for a radical demonstration of Bernoulli's Principle. A further refutation of the Bernoulli analogy was that when lift forces were measured during the stage of swimmer's acceleration, those forces, although small, were not even in a direction that would contribute substantially to forward propulsion.

The contention that Bernoulli's Principle is the appropriate model for explaining propulsion in swimming is not justifiable. It is a tragedy that it has remained popular for so long for it has led those who theorize without validating their assumptions down an incorrect path of inquiry and postulation. Bernoulli's Principle is simply an inappropriate model for explaining propulsion in swimming. Sprigings and Koehler (23) reacted to the lift-force-only postulation as follows: "...to dwell exclusively on the lift component without any attention to the drag component would be an analytical blunder".

**Lift and Drag Forces**

It is generally recognized that drag and lift forces have to be considered as contributing to the propulsion of swimmers. To emphasize lift and minimize drag as quoted above is nonsensical. Swimmers should maximize forces that produce propulsion. Sprigings and Koehler (23) proposed an explanation employing Newton's Second and Third Laws to account for drag and lift forces in swimming. As a swimmer pushes backward, the fluid under the hand is slowed by the angle of the hand (angle of attack) and frictional forces. When the angle is acute, the slowing is small producing small lift and drag forces. When the angle is larger, the slowing increases as does the reaction force. The reaction force can be broken down into lift and drag components. The slowing of the fluid in this manner is also embellished by frictional drag of the surface of the hand and forearm as well as the form drag caused by the size of the hand and forearm as it moves through the water. Wood (28) explained this phenomenon as follows:

When a body moves through a fluid the force acting on it does so directly backwards and is called drag or form drag. As the oncoming fluid strikes the body it is deflected outwards and attempts to follow the body contour. In the case of a streamlined body it is able to do this relatively easily. In the case of a nonstreamlined shape, for example, an oar or a paddle or a hand held so that as much cross sectional area as possible is positioned perpendicular to the line of flow, the fluid is unable to achieve the sharp turn at the edge of the body and flow separation takes place giving rise to whirling and eddying pockets, or a wake behind the body extending in the direction of the flow.

An interesting feature of these pockets is the low pressure which is obtained in these volumes. This low pressure coupled with the build up of pressure as the fluid strikes the front of the body leads to a resultant pressure in the original direction of the fluid flow. This resistance is called form drag.

The Newtonian interpretation of propulsion through water is based on the impulse-momentum relationship (Newton's Second Law). Basically, any change in the magnitude or direction of the water's momentum as a result of its disturbance by a swimmer's body segment(s), is a direct result of an impulse (i.e., force applied for a period of time) applied to it. Newton's Third Law dictates that there must be an equal but opposite impulse back on the swimmer's segment(s) that is then broken down into two perpendicular components, lift and drag. Drag is the force component parallel to and in the same direction as the relative fluid flow prior to segment contact. Lift is defined as the component of force perpendicular to the drag component. To use the Newtonian approach to understanding propulsion, one only has to visualize the resulting changes in magnitude and direction of the disturbed water's momentum as it moves (relatively speaking) past the swimmer's segments, and then apply Newton's Third Law. On the other hand,

![Figure 4. The components for assessing propulsive forces from a lateral perspective. The line of flow is the direction in which the hand moves. The drag force acts opposite and the lift force acts at 90 degrees to the line of flow. A resultant force is derived from the drag and lift forces. The angle of attack of the hand in this example is its angle to horizontal. No indication is given to the line of propulsion because arm actions may be contributing to propulsion as well as reacting to another body movement. It is incorrect to infer that the line of flow should always coincide with the line of propulsion.](image)
Bernoulli's Principle is based on the work-energy theorem which imposes serious limitations on its ability to predict lift in a practical situation such as the swimming stroke where turbulent flow predominates. It should be recognized that Bernoulli's Principle is not capable of predicting drag forces.

In still water, drag acts in the opposite direction to the line of motion of the foil (i.e., hand and forearm) and it resists the motion of the foil. Figure 4 illustrates the various components to be considered with the forces that occur on the hand and/or forearm in all competitive swimming strokes.

Using the Newtonian model, drag is composed of three parts: induced drag, frictional drag, and form drag. Each is related to the angle of attack and are combined to form the "coefficient of drag". This model can be used to predict both drag and lift components of force in the action of a hydrofoil (i.e., a swimmer's hand and forearm).

The major consideration in this interpretation is the direction in which the hand is moving. That direction is the flow line. Drag forces react directly opposite to the flow line and lift forces react at right angles. Figure 5 illustrates some of the force directions generated by positions of the hand in a crawl stroke. The data for the figure were obtained from Wood (28). It can be seen that how the hand is pitched determines the direction of the forces that are created.

The data in Figure 5 are limited but do represent the features of a crawl stroke action. The major limitations are: (a) it is a two dimensional representation and thus, it is not an analysis of the only forces that occur; (b) the data are simulations of the actual stroke positions; and (c) the speed of swimming is slow. Despite these limitations, several features are notable.

1. When the hand is providing force that causes the swimmer to accelerate (i.e., propulsion occurs), drag forces are dominant and roughly in the direction of intended movement.

2. When lift forces are dominant (i.e., as the hand

Figure 5. The path of the mid-point and angle of a hand in crawl stroke (from Wood (28)). The force lines, L and D, indicate the direction in which they are acting and the comparative size of the two force bars indicates the contribution of the forces at each stage of the stroke. The velocity graph indicates hand speed at each position. It should be noted that in the first five positions, the lift force is in a distal orientation. The swimmer is accelerating at positions 6, 7, and 8 when drag forces are greater than lift forces.

Figure 6. Various depictions that attempt to sustain the belief that Bernoulli's Principle is appropriate for swimming. "F" indicates the supposed direction of forces created. A: illustrates an ideal airplane wing that creates no turbulence. A lift force, at 90 degrees to the airflow, is the only force generated because of the deviation of flow over the cambered wing top. B: illustrates an invalid analogy of the same principle applied to the hand (adapted from Counsilman (9)). C: illustrates what really is likely to happen to the hand when it slides directly sideways in the water as depicted in B. Its undesirable foil shape creates water deviations in two directions and also creates turbulent drag which results in the swimmer going in the direction of the line of flow. In the C example, any lift force is probably very small because of the two deviations.
moves forward and downward), the lift occurs distally, that is, from the finger tips along and up the arm. That occurrence does not agree with any depiction of the hand as a hydrofoil to explain Bernoullian lift. In those illustrations it is usual to suggest that flow over the radial edge of the hand is the asymmetrical wing that produces the lift. Those illustrations simply are wrong and do not occur during this phase of the pull (see Figure 6).

3. Cappaert’s analyses of world and Olympic champion swimmers have shown that propulsion is achieved only when some facilitating and major component of drag force occurs in all strokes other than breaststroke (3). In the reaching forward and down action in the crawl stroke that is so common in many stroke patterns, a force that retards the swimmer is produced. That finding is important despite the assumption that a lift force is created (28, 29).

What exists in swimming actions are combinations of lateral and longitudinal forces of both lift and drag. They occur because swimmers do not pull their hands straight back through the water. There is some element of sideways movements in most patterns. In breaststroke sideways movements are accentuated. However, since Counselman (7) published pictures of swimmers under water and used those pictures to support the importance of sideways actions (i.e., Bernoullian lift), stroke patterns have changed and performances have improved remarkably. Figure 7 compares underwater pull patterns, taken from directly below the swimmer, in the butterfly stroke of Charlie Hickox (7), who recorded the best time in the world for 200m butterfly in 1967, and Pablo Morales (3) as he swam to victory in the 1992 Olympic 100 m butterfly event.

What is noteworthy about these patterns is the reduced lateral aspect of Morales’ action when compared to that of Hickox. It is not known when Hickox achieves a propulsive force but it is known for Morales. When Morales is propelled by the arms, his pull is notably direct. The S- or hour-glass shaped pull as proposed in the 1960s is not evident. There is a constant, slightly outward pull path in Morales’ action that is most probably caused by adduction of the upper arm and positioning to use extension of the arm in the latter phase of the pull. That is an important phenomenon because often the arm movements of swimmers are modified to accommodate the limitations of the human anatomy.

**Figure 7.** The finger tip tracings, from a camera’s view directly below two swimmers, of Charles Hickox during training (adapted from Counselman (7)) and Pablo Morales in his 100m victory swim at Barcelona, 1992 (from Cappaert (3)). It can be seen that Morales has a more direct stroke, facilitating greater drag forces, than does Hickox. The start of propulsion for each of Morales’ hands are indicated by the points $P_s$ and continue until the end of the tracings which is where the hands leave the water. The two arrowed straight lines indicate the lines of propulsion for each swimmer.
which is poorly constructed for swimming. Given Morales pattern of pull and hand orientation, no Bernoullian lift could account for the propulsive forces achieved or demonstrated.

Another feature of these two pulling patterns is the asymmetry between the arms. There are actions added to an ideal pattern to offset modifying forces so that there is continual propulsion of the swimmer in a straight line. For example, a strong arm is compromised to balance a weaker arm. Because of that compromise, it will be very difficult to find a perfect pattern of movement in any swimmer. At best, modern champion swimmers usually will have a better approximation of an ideal pull than will lesser performers.

The case has been made that Bernoulli’s Principle is inappropriate for a basic understanding of the propulsive forces in swimming. A return to Newtonian Laws is warranted. However, that return requires the consideration of drag and lift forces rather than the 1960s’ version of contemplating only drag forces. Evidences of a scientific and observed nature are available to support and extend this restated position.

**Further Considerations**

*The minimal contribution of lift forces.* If lift forces were working fully in the Bernoullian mode, the flow of water across the back of the hand would be undisturbed, that is, the water would be as clear as it is on the palm of the hand. However, anyone who has observed swimmers’ pulls underwater can recognize that the “trailing” water on hands is often turbulent and containing bubbles. That means the water behind the hand is being “dragged” in an eddy and is not the clear flowing form necessary for Bernoullian lift. Valiant et al. (27) explained this observation:

... bubbles and turbulent wake about the hand suggest there is very little opportunity for attached flow, meaning a low potential for creating a lift force component.

When observations of turbulence and bubbles are made, lift forces will not be dominant in contributing to propulsion.

Holt and Holt (11) tested the hypothesis of flow across the back of the hand generating lift. They attached several fin-like baffles to the back of swimmers’ hands. The baffles effectively disrupted the flow across the curved back of the hand and thus, negated lift forces. The effect on crawl stroke swimming speed was minimal (2%). This demonstrated that lift forces were quite minor in their contribution to propulsion.

Figure 8 illustrates Kieren Perkins’ left hand pull paths from side, front, and bottom perspectives during the

![Figure 8](image-url)

*Figure 8.* Four perspectives of the position of maximum propulsion in Kieren Perkins’ left hand during the final 100 m of his 1500 m victory swim at Barcelona. The lines with letters attached indicate the lift (L), drag (D), and resultant (R) forces and their directions. The paths of movement for the middle finger are indicated with small arrows. Box 1 shows the force curve for the entire stroke. The heavily shaded area is the propulsive force that is imbedded in the total force produced. Peak propulsive force occurs at frame 15 which is equivalent to f16 indicated in each of the other boxes. Box 2 is the side view with a distinct horizontal component once the hand has reached an appropriate depth. The drag force is markedly greater than the lift force as well as being in a more beneficial direction. The pitch of the forearm to horizontal is 90 degrees suggesting that its contribution to propulsion is close to being drag only. Box 3 is the frontal perspective of the pull showing only a slight sideways movement, mostly to accommodate clearing the hip on exit at the end of the pull. Drag and lift forces appear to be closer in direction and magnitude than in the other two boxes. Box 4 is the view from below the swimmer. The path of the pull is comprised of two straight line sections. The first is a direct pull and the second has a lateral component which is required to clear the hip on exit. The drag force component is much larger than the lift force and also in a more beneficial direction. At this point of maximum propulsion, no case can be made for the stroke being governed by only lift forces. It decidedly is a drag force dominant propulsion.
last 100m of this 1500m gold medal swim at Barcelona. It can be seen that the path of the finger tips and the position of the hand at the position of maximum pulling force produce more drag than lift force. The drag component is also aligned more in the desired direction of propulsion than is the lift component.

The hand angles in all strokes usually never approach the theoretical best angle for developing lift (37 degrees (9)). That angle is not exhibited by the hands of top swimmers in either the vertical or lateral planes during propulsive phases of the pull (see Figure 8 for an example). It should be noted that proposing such an angle is contrary to the required position for Bernoullian lift to occur. Such an advocacy is a further illustration of the confusion that has surrounded lift and drag forces and Bernoulli’s Principle.

The hand-forearm propelling surface. Much of the discussion on propulsive forces has concentrated on what the hand does. However, it is very possible that the forearm provides an effective propelling surface as much as does the hand. Coaches have often talked of the "elbows up" position to produce propulsion but often in the context of placing the hand in a better position. However, swimmers are still able to propel themselves forward quite satisfactorily if they swim with a good elbows up position, that is, the forearm is vertical and pushing backward, with fists clenched or hands turned sideways to slip through the water. The role of the forearm in contributing to propulsion needs to be considered more than it has been. If the forearm is effective for contributing to propulsion then those adhering to Bernoullian forces cannot explain its contribution. The forearm is not a lifting surface and it has never been included in any swimming descriptions of lift production.

Cappaert analyzed the lift and drag forces generated by the hands and hands plus forearms in various positional angles and speeds of water flow (25). That study was oriented towards focusing on lift forces and in its discussion maintained that orientation. Coefficients of drag and lift as well as absolute forces were measured (see Figure 9). Contrary to the emphasis of Cappaert's discussion, the following factors were demonstrated.

1. The coefficient of drag was always higher than the coefficient of lift at all angles of pitch. That finding is in accord with Wood’s study in the mid-1970s (28, 29).

2. The forces created by the forearm and hand together were always greater than the hand alone.

3. The contribution of the forearm to lift forces was always greater than the hand at all speeds.

4. The contribution of the forearm to drag forces increased as the speed of swimming increased and surpassed those of the hand at 2 m/sec.

Figure 9. The contributions of the hand and forearm to lift and drag forces at three speeds. The total forces of lift and drag are compared in the third graph (adapted from Troup (25)). At 2.0 m/sec the forearm contributes the greatest proportion to lift and drag forces. In graph 3, at 2.0 m/sec the contribution of drag forces is 84% and lift forces 16%.
5. As the speed of swimming increased, the contribution of the hand-forearm to propulsion rose dramatically for drag and barely for lift. At 2 m/sec the drag forces accounted for 84% (38.1 Newtons (N)) and lift accounted for 16% (7.3 N) of the total force. Cappaert's values were derived out of context for swimming and subjected the hand and forearm models to the same water velocities. However, in most less-than-perfect swimming strokes, when rotation of the arm occurs, the hand usually moves faster than the forearm. That would mean the forces on the forearm would be associated with a speed that is slower than that of the hand. The difference in speeds for relatively effective pulls is not great. Thus, even though the values illustrated are not derived from actual movements, the implications of the findings are still valid (J. M. Cappaert, personal communication).

The maximum contributions of drag forces. The side view of pulling patterns of some of the world's best swimmers are presented (see Figure 10) indicating the phase of the strokes where propulsive forces are created (extracted from 3, 24). Propulsion occurs when there are distinct accentuations of backward rather than lateral forces. This means that champion swimmers are pushing back against the water rather than emphasizing lateral movements to generate lift. An example of Summer Sanders' crawl stroke analysis is available (24). In both her left and right hand pulls, which exhibited S-shaped patterns, when sideways components were exaggerated her propulsive force decreased. Sideways actions did not facilitate effective propulsion. It should be noted that Summer Sanders' crawl stroke was not reputed to be one of her better strokes.

Coaches are encouraged to conduct their own experiments comparing lift versus drag orientations. They should instruct swimmers to emphasize pushing back against the water so that the hand-forearm combination becomes fixed in the water. It should be pointed out to the swimmers that they are to move their bodies past the fixed position in the water. This should bias the swimmers' strokes towards generating drag forces. Times and number of strokes taken for a distance should be recorded for that orientation. Then swimmers should be instructed to move their hands-forearms through the water in exaggerated S-shaped patterns. That action should facilitate an increase in lift and a reduction in drag. Times and number of strokes taken for a distance also should be recorded for this orientation. The two orientations should be compared for time and number of strokes taken. Swimmers also should be asked which orientation felt best and made them swim fastest. The outcome of this test will be obvious but coaches will also be surprised by the magnitude of the differences.

Pulling patterns. The observed pitch of hands of champion swimmers are more in the range of angles that maximize drag force rather than lift. That contention is supported in data contained in the technical summary of Cappaert's work (4). It should be noted that hands are rarely, if ever, pitched at 90 degrees. Hand pitch not only has to accommodate propulsion but also has to "correct" for vertical movements involved in hand recoveries and repositioning, breathing, and kicking. All strokes require compromise positions and can never be solely dedicated to propulsion.

What was shown in Cappaert's analysis was an objective verification of the findings of Wood's and Holt's studies. The primary force in the propulsive phase of crawl, back, and butterfly strokes is drag. Any lift force is minor but still important. That one or the other force is totally responsible for propulsion was never found. A reason for this phenomenon was offered by Wood (28):

When the recovery in front crawl is cleared from the water and begins to swing up, out, and
forwards, the body is subjected to a rotational effect. This in part is canceled out by the leg beat but also creates a reaction in the pulling arm which, as it begins the forward and downward sweep is often seen to move laterally and consequently forces of lift and drag will be generated.

The swimmer then may be making propulsive use of a deviating pull path which is produced not as a result of a random search for still water, but as a patterned action based on a specific mechanical or anatomical principle.

The middle section of the front crawl pull path is characterized by a marked inward and upward sweep of the hand and forearm, which takes place as a reaction to the rotational effect of the body around its long axis as the opposite arm and shoulder swing into the entry.

In back crawl the characteristic J-type pull, with the hand sweeping up towards the surface as it pulls, is caused simply by the action of bending the elbow. This occurs to allow a greater propulsive force application and as the elbow moves downwards the hand in reaction moves up.

There is a degree of eloquence about this simple explanation for sideways components in swimming pulls. They occur because of the structure of the human anatomy. Rotational forces are developed by recoveries that sweep to the side in crawl stroke, by a body rolling action that approaches 90 degrees in both crawl and back stroke, the adduction of the humerus in the shoulder joint in the middle of the action, the need to move the hands out from under the body so that a recovery can be effected in butterfly and crawl, and the forces created by the head turning in the crawl stroke breathing action. Those forces have to be counter-balanced by lateral actions of the kick and/or pull. When they occur in the pull, they are done as a reaction to keep the swimmer on a straight path, not to develop lift forces. Those forces are a consequence of the reaction. It is possible that if the human anatomy was structured differently, no lateral component of any pull would occur; the body simply would strive to generate a total drag force to achieve propulsion.

Cappaert’s work and the accommodation-of-the-anatomy hypothesis of Wood, indicate that the primary force of propulsion in direct force strokes is drag. That interpretation is supported by the earlier work of Wood and Holt.

When an arm is in the water it is not always contributing to propulsion. Only when certain directions of action and pitch of the hand exist is propulsion attained. Thus, it is only appropriate to look at part of the pull to determine what is important for propulsion. The rest of the time the arm is in the water it is increasing frictional, form, and possibly wave resistance. It would seem to be prudent for a swimmer to minimize the time that an arm is creating extra resistance and to maximize its time in propulsion. Several figures already presented (see Figures 8 and 10) show when propulsion is initiated and when it ceases for several champions.

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**Figure 11.** Tracings of the crawl stroke actions of single arms of two swimmers highlighting the stage of the movement that produced acceleration (labeled AC). Propulsion occurs when drag forces are dominant (adapted from Valiant (26)).
Valiant (26) analyzed the progression of crawl stroke swimmers using an accelerometer. By matching filmed sequences with synchronized records of acceleration he was able to describe the parts of the arm stroke that contributed to forward progression. Figure 11 illustrates the phases of the crawl stroke in two swimmers that covered the duration of the acceleration records. Those patterns are very similar to the stages of propulsive force indicated in Figures 7, 8, and 10.

It is safe to assert that drag forces are predominant in the propulsive phase of the crawl, back, and butterfly strokes in swimming.

Measurement. The measurement of forces in swimming is difficult. Interactions occur between the many segments involved in normal actions. When an analysis is performed on an isolated segment, misleading conclusions could be developed. Even though the current status of force measurement is much better than it was, it still leaves much to be desired. In this paper we have discussed measurements that are in concert with observational analyses of filmed records of swimmers.

The early and later stages of the pulling pattern exhibit a rounded movement path of the hand-forearm that conserves momentum. Observations and reports from swimmers would suggest that these early and late stages of pull—which we will refer to as "transition" stages—are predominantly in the vertical plane, and are not effective in producing propulsion.

Current computer analyses of forces are limited. They analyze the hand only and treat it as an isolated object, not being affected by the forearm or any other part of the anatomy. The entry transition stages of crawl stroke and butterfly generate a small lift force because the hand-forearm can be pitched to produce: (a) a lift force that is developed through distal flow that is aligned forward, and (b) a relatively small drag force that has a very high vertical component. The resultant force from those two components could have some beneficial propulsive contribution even though a significant portion of it is in a vertical orientation. Wood and Holt (28, 29) have shown that forces which could contribute to and do not impede propulsion are developed if the entry transition movement is markedly downward.

The path that the hand-forearm takes in the underwater phase of a swimming stroke does not always facilitate propulsion. There are forms of action that actually hinder, rather than help, a swimmer. Any time a component of movement is fractionally or more in the forward direction, a swimmer’s progress is partially checked. For example, when a hand enters and continues to extend forward under water in crawl stroke, drag resistance is increased and forces are created that work to reverse propulsion. Those detrimental forces detract from the overall efficiency of the swimming stroke and are counterproductive to forward propulsion.

The current techniques of force measurement and estimation for the hand in the entry transition and the body of a pull are satisfactory estimates of what the hand is doing in its contribution to propulsion. However, in the estimate of the exit transition there is a profound weakness that suggests measurements at that stage of force estimation should be viewed cautiously.

In the entry transitions of crawl stroke and butterfly pulls, the force is created distally, that is, the water flows from the fingers up the arm. However, at the exit transition, it is the wrist that leads the hand. This means that the flow characteristics of the water past the hand during this stage are considerably different from that experienced at hand entries. It is likely that considerable turbulence will surround the back of the hand which is not an environment conducive to producing lift.

Measurements of the exit transition forces of the hand have been provided by Cappaert (3, 4). Her analysis considers the hand to be an independent object not attached to an arm. It is treated as a discrete segment. Thus, it is possible to determine angles and velocities of movement and calculate lift and drag forces. However, that is a spurious procedure. The hand does not function as an isolated object because of its trailing position. Cappaert’s analyses illustrate high lift forces and smaller drag forces for that stage of propulsion in almost all crawl stroke and butterfly swimmers. It should be understood that those measures are theoretical and must be viewed with some skepticism because of the confounding influence of at least the forearm. Because of that weakness, we advocate that measures which are reported for the entry transition and the body of a pulling pattern can be considered, however, measures for the exit transition should be ignored until better forms of force estimation can be developed.

When the pulling action can be made in a largely horizontal direction, the orientation of the hand-forearm favors stronger drag forces the more it approaches right angles to the line of propulsion. A pure right angle may not be the most beneficial position while a pulling pattern has the dual function of creating direct propulsion and counteracting rotational forces in any of several directions. Kieren Perkins’ (see Figure 8) and Krisztina Eggerszegi’s (see Figure 10) hand-forearm positions produce very large drag forces in comparison to lift forces. Their positions approach right angles to the intended direction of propulsion. On the other hand, as the angle of the hand-forearm lessens in relation to the line of flow, the drag forces diminish and lift forces become relatively more important (see Hrvoje Baric in Figure 10).

When entry transitions go too deep, the stroking pattern of the body of the pull will likely slip upwards either gradually or in steps. Because of the noticeable vertical component rather than a maximized horizontal orien-
tation, drag forces will be reduced and potential power from a better path of movement lost. It is advocated that the tendency to dig deep on the entry should be avoided so that energy expended will be used more efficiently and effectively because of the better alignment with the line of propulsion.

The proportional contribution of lift and drag forces to propulsion in the intended direction of progression is dependent upon a number of factors:

(a) the phase of the pull;
(b) the angle of the hand-forearm to the line of flow;
(c) the angle of the hand-forearm to the line of propulsion;
(d) the contributions to the resultant force and the direction of that force;
(e) the pitch of the hand-forearm; and
(f) the rotation of the hand-forearm.

The concepts employed in measuring forces in swimming have been narrow and limited. As pointed out above, measurements usually have been restricted to theoretical force measurements on the hand. However, there are other strategies and data items that are important.

1. The acceleration and deceleration of the center of mass is important. If forces derived from the hand-forearm combination and kicking were correlated to acceleration, it may be easier to determine the boundaries of effective action.

2. The influence of the kick has to be considered. It allows the hand-forearm to generate greater forces and, particularly in backstroke and butterfly, could contribute to the development or maintenance of forward propulsion. Its contribution in breaststroke is obvious.

3. The situation where one arm is in the water and extending forward (as is often the case in crawl stroke and backstroke), while the other arm is generating propulsion, has to be factored into any calculations. The force created by the propelling arm could be increased by deducting the negative resistive force generated by the extending arm.

4. It is important not to lose sight of the primary purpose of force measurement in swimming. It indicates the magnitude of effect. Force sizes should then be related to what a swimmer is doing anatomically. Effective forms of movement should be described. It might be possible to determine if even further improvements are possible, particularly if the observed movements do not use the anatomy in an optimal manner.

The above four considerations are only some of the possibilities for analyzing the complexities of swimming propulsion and resistance. Technologies are now emerging that will allow direct measurements of forces and accelerations to be more feasible than in the past.

**Breaststroke.** There have been several references made that indicate drag force is more important than lift force in competitive strokes other than breaststroke. However, in breaststroke the lift component of the forces in the arm pull is increased. That is because of the very accentuated sideways movements in the outward and inward scull phases of the pull. Because of reasons cited previously (e.g., the inadequate leading and trailing edge shape of the hand and forearm) it is still not appropriate to use Bernoullian reasoning for the actions that are observed. A far more direct and visual understanding of both drag and lift components can be achieved using a predictor model based on Newton’s Second and Third Laws.

Breaststroke swimming does not follow the similarities in force generation of the other strokes. The arms' movement paths have a very dominant lateral component. However, the forces acting on the hand-arm combination are similar to those in the other strokes. What is different is that the direction of the drag force is very much to the side and contributes little to propulsive forces. Once the arms move directly sideways or have any forward component on the insweep, the drag force does not contribute to forward progression. The resultant force from the combination of both drag and lift forces on both arms will generate propulsion. Drag forces are not of great concern because each arm's force will mostly cancel out that of the other. Figure 12 illustrates the force curves for Mike Barrowman in the 1992 Olympic Games 200m final. It is interesting to note that for both arms the total resistance of the hand and arm on recovery exceeds the amount of force created during the pull.

**Practical Implications**

It is time for most swimming science educators and practitioners to alter their thinking about pulling patterns of swimming strokes. The acceptance of Bernoullian lift as an "explanation" for the major propulsion forces has led to a tolerance for large lateral movements in pulling patterns. It has been argued that such movements do not maximize propulsive forces and are not demonstrated by today's best swimmers. Some lateral movements: (a) have to be retained to react to various forces that are not in the line of intended direction, and (b) are necessary because of the imperfections of the human anatomy for developing efficient force production. This orientation will require a different teaching and coaching strategy to the one that is popularly espoused.

1. Swimmers should not be taught or encouraged to produce exaggerated S-shaped, “question mark”, hour glass, etc. pulling actions. Such an approach will reduce propelling effectiveness, not enhance it.

2. Swimmers should be taught or encouraged to feel that they are pushing against the water in a predominantly backward direction. It is possible for swimmers to
emphasize that orientation but still retain the minimal amount of lateral deviations that satisfy anatomical and reaction accommodations. That is different to encouraging lateral movements which reduce efficiency. Promoting "direct-action feel" and tolerating minimally necessary lateral movement components will go close to maximizing propulsion and minimizing wasted energy and resistance. Lateral movement components should occur naturally, whereas direct force components should be emphasized.

This does not imply that lift forces are not important or should not occur. Drag forces should not be exclusively emphasized. The best propulsion will result from a stroke that has an optimal combination of both drag and lift force components such that their combined contribution to the forward direction is maximized for the energy expended.

3. The role of the forearm as the major propelling surface should be stressed. That role increases as the speed of the swimmer increases. When swimmers are swimming as fast as possible, their attention should be on what the forearm is doing with the hand being considered as a simple extension. That will increase the propelling surface and consequently, the size of the drag forces created. The forearm is marginally more important than the hand in propulsion.

4. It is better to talk of Newton's Laws as the underlying reasons for swimming propulsion than Bernoulli's Principle. Newtonian Laws can account for a greater amount of the phenomena and actions observed in swimming. Bernoullian reasoning is misleading and incomplete. It is an inadequate model for describing the propulsive forces in swimming.

5. The actions of the arms in developing propulsive forces have to be balanced with the resistances that exist in the stroke. It would be inadvisable to increase resistance while increasing propulsive forces. Resistance increases much more rapidly than does speed. The latter part of this paper discusses various forms of resistance and their effect on swimming speed. It is advocated that maintaining minimized resistance is of a greater priority than is increasing propulsive force through extra effort or exaggerated movements.

Figure 12. Left and right hand force curves and movement patterns for Mike Barrowman during his 1992 Olympic final swim in 200 m breaststroke. On the force curves, the area under the dark line is the propulsive force and its magnitude in Newtons. The hand positions depicted correspond to the second data point (#1) on the base axis of the force curve. The first path ("S Side") is the lateral movement of each hand. Arrows indicate movement direction. The second path ("S Fwd") is hand movement from a frontal perspective. The rightmost path ("S Bot") is the hand movement from the perspective of looking up from underneath the swimmer, that is, from the pool bottom.
Propulsion

Although this paper and previous research have focused on the hand as the origin of forces, we have proposed that the forearm functions as a propulsive surface. Since the hand and forearm are jointed, it is appropriate to consider each segment independently for propulsive properties. One cannot assume that what happens on the hand also happens on the forearm. It is possible that the forearm could be very effective in its propulsion while the hand could be pitched differently and not as efficient. Consequently, it is important to consider both segments independently for effectiveness. That will require a radical change in the way measurements and forces on swimmers' arms are described. When that is accomplished, it is expected that the case for drag force dominance (in three of the four strokes) and Newtonian interpretations will be even stronger.

As an example of the above point, Figure 8 illustrates Kieren Perkins' forearm being pitched vertically while his hand is offset at a slight angle. The lift and drag force sizes and directions would be different for each arm part. On the other hand, Hrvoje Baric's arm (see Figure 10) is pitched at a very low angle decreasing the effectiveness of drag forces and increasing the relative contribution of lift forces. Since the alignment of the forearm and hand is almost straight, the contributions to propulsion of each arm segment may be different in size but are quite likely to be similar in direction of effect.

Understanding the forces that contribute to propulsion is not a simple matter. It is not just a case of saying that drag forces or lift forces are only important. It is more a matter of understanding the complexity of the movements in all strokes and then evaluating the positions of the anatomy which create favorable forces that contribute to forward propulsion. When those actions are correlated to the actual stage in the pull pattern where the center of mass is accelerated is even more important. However, it would seem that several factors regarding force production need to be considered when evaluating pulling techniques.

1. Produce a pattern that allows a substantial drag force to be created for as long as possible given the requirements to round into the initiation and out at the termination of the action. This is advocated because the potential to increase drag forces is much greater than for lift forces.

2. When the pull is generally in a horizontal direction, the pitch of the hand-forearm should be close to a right angle to the direction of propulsion while the rotation of the hand should be that which accommodates lateral requirements.

3. In strokes other than breaststroke, reduce or eliminate any underwater movement that has any slight forward thrust.

4. Attempt to achieve a feeling of “pressure” on the hand that comes from slowing the water so that drag forces will be initiated and maintained for as long as possible.

5. When the vertical component of the pull pattern is substantial, as in the transition phases, orient the hand-forearm so that lift forces will be as large as possible and minimize the time spent in this orientation (but without creating any sudden or jerking actions).

This discussion of propulsive forces has attempted to present a status report on the principles involved in propulsion in competitive swimming strokes. Drag forces are the major important components of propulsion. Lift forces exist but are of minor magnitude and usually operate in a direction that is not particularly helpful for propulsion. Objective measures of forces and the analyses of modern champion swimmers confirm this position. With regard to the theoretical basis of the forces, the originally proposed Bernoullian Principle is found to be inappropriate and insufficient for accounting for the propulsive forces. An application of Newton's Second and Third Laws provides a better basis for understanding what occurs. A change in the general thinking of the majority of biomechanists and coaches involved with swimming is in order.

Resistive Forces

When swimmers are not creating propulsive forces of sufficient magnitude, they slow down. It is frequently observed that some individuals seem to slip through the water requiring less effort than others. Some swimmers look to be swimming well at slow speeds but when they attempt to speed up they do not improve as much as others. One of the explanations for such differences could be the amount of resistance, more commonly referred to as "drag," that is created by the swimmer.

Karpovich (13) described three forms of resistance in swimming: (a) skin friction which is analogous to the "stickiness" of the swimmer for moving through the water, (b) eddy resistance, the amount of water that is sucked along behind a swimmer as forward progression is achieved and is proportional to the cross-sectional area that is pushed against the water, and (c) wave-making resistance which is caused by swimmers' movements that move large amounts of water (e.g., excessive diving of the shoulders and body at the butterfly entry). That classification, as is explained later, is meaningful to coaches. However, for a period of time swimming researchers followed the task of finding about passive and active drag (5). Passive drag is the amount of resistance that exists when a swimmer does not move. Active drag is the resistance created by movements and
is added to passive drag. Others directed attention to partial causes of resistance. For example, Counsilman (9) drew attention to (a) head-on or frontal resistance, (b) tail suction or eddy resistance, and (c) skin friction. It should be noted that frontal and eddy resistance are features of the same category of resistance, namely form drag.

It is important to consider resistance in terms of swimming performance. If resistance can be minimized, then the propulsive effects of a swimmer's efforts will be maximized. The coaching of swimming technique should focus on actions that increase swimming speed and decrease impedances to progress.

An understanding of resistances is an important feature of modern swimming and coaching. It is a topic that is starting to have resurgent interest and is now considered to be more important than previously thought. It appears that reduction in drag is a preferred approach to improving speed through the water than is performing some subtle adjustment to technique. An emerging coaching approach for technique appears to be to perform propelling actions but not at the expense of creating any unnecessary drag. If a choice is to be made, it should be to preserve the minimum drag position and action over attempting any "stronger" action that could cause the drag (resistance) to increase. That is a very different approach to coaching stroke technique than is entertained by most coaches.

Resistance should be as low as possible on all parts of the body except the forearms and hands. Since they should attempt to create the greatest amount of drag force possible, their surface and position should maximize drag resistance. The conclusion is that drag forces should be minimized in most of the swimming action except for those surfaces which contribute to propulsion.

Sheehan and Laughrin (21) recently drew attention to the classifications of resistance that were highlighted by Karpovich. They described their qualitative and quantitative effects as well as suggesting how they should be measured. The benefit of classifying three types of resistance is that each has direct application to coaching techniques. When only categories of active and passive resistance are used, they are too general to cover meaningful concepts for coaching. Sheehan and Laughrin's classifications are described below.

Frictional Drag

Frictional or surface drag is developed when water passes over a rough surface. This is part of passive drag. Skin roughness, body contouring, hair, and swim suit fabric are examples of the roughness that creates friction as a swimmer moves through water. The relationship of frictional drag to velocity is linear, causing a minor effect upon performance as speed is increased. Figure 13 illustrates the major features concerning frictional drag.

The secret of reducing skin/suit-friction drag is to maintain laminar flow, a condition where the fluid glides smoothly over the surface. Water in laminar flow behaves as if it was a sandwich of many sheets, each one sliding smoothly against its neighbor. The boundary layer closest to the skin is pulled along nearly at the speed of the surface itself while the layer furthest away is hardly in motion. The entire sandwich of layers influenced by the surface itself is quite thin, but if it
FRICTIONAL (SURFACE) RESISTANCE

1. SKIN WITH HAIR (ARMS); ROUGH SUIT

Eddies and turbulence absorb energy and results in higher frictional resistance.

2. SMOOTH SKIN BUT WATER REPELLENT (OILED) SURFACE.

The resistance of the oiled skin repelling the water is greater than the friction of the water on the skin.

3. SMOOTH GRANULATED SURFACE (SHAVED SKIN).

A thin layer of water (boundary layer) adheres to the skin and is carried along with it. Each microscopic layer thereafter moves slightly faster until full water speed is reached. Friction is water on water and therefore much less than water on skin.

4. RELATIONSHIP OF FRICTIONAL RESISTANCE TO SPEED IN WATER.

Linear relationship.

Figure 13. Features concerning frictional drag in swimmers. The major implication is that the greater the amount of water dragged along by the swimmer, the greater will be the frictional resistance.
is in laminar flow, it provides lubrication allowing the body to slide through the water. It is very difficult to establish laminar flow. The slightest irregularity, a bump, sharp edge, or natural roughness is enough to spoil laminar flow and cause turbulent flow. Turbulent flow, in which water in contact with the skin or fabric swirls violently in a tangle of microscopic eddies, causes friction that robs the swimmer of speed, power, and efficiency. It is unlikely that the human body can attain laminar flow in all but a few minor places. For swimming efficiency, it is probably better to attempt to reduce turbulent flow which will result in better “sliding” through the water.

Frictional drag can be reduced by shaving hair off the body and legs, but not the forearms. The reduced resistance causes a reduction in the energy per stroke when compared to an unshaven condition (20). Tight swim suits of sheer fabrics with a structure that minimizes seams and edges is another way of reducing frictional resistance. Wearing a latex cap also provides a smoother surface than does a head of hair and thus, further reduces drag.

It must be emphasized that the frictional surface must not be perfectly smooth, but rather, have a fine texture that holds a thin water film which becomes part of the swimmer and is carried along. That results in friction only being between water and water which is much less than between a very smooth skin and water (12).

**Form Drag**

Form drag is caused by the shape (geometry) of the swimmer and is the second component of passive drag but may also be part of active drag. To a minor extent, it is affected by the density of water and is part of the explanation of the difference between salt and fresh water performances. Figure 14 illustrates the major features concerning form drag.

The largest factor in shape is the cross-sectional area (frontal resistance) of the body. Form drag increases by the square of the velocity and so becomes increasingly important and influential the faster a swimmer travels. However, form drag is not always detrimental. It contributes to hydrodynamic lift and is critical to propulsion in some strokes. In fact, it is critical to propulsion where it is accentuated on the hands and forearms, and in some circumstances, the legs and feet. Form drag
FORM (CROSS-SECTIONAL) DRAG

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

Two components are frontal and eddy resistance.

Relationship of form drag to speed in water.

Quadratic relationship.

Figure 14. Features concerning form drag in swimmers. Four examples of increasing and decreasing streamline are shown. A: a head-up position (hyperextension of the neck) in crawl stroke tends to curve the spine and sink the hips lower than necessary. Straightening the neck (looking to the bottom) produces a more favorable streamline. B: crossing the entry behind the head in backstroke causes a hip movement from side to side, increasing form drag. If the entry is made at a position where streamlining is not disrupted, form drag should be minimized. C: the head-up position of the breaststroker causes the hips to sink increasing form drag. That problem is accentuated if the arm action occurs under the body. When the arm action is well forward of the torso and the head looks down, form drag is minimized. D: excessive head lifting and neck hyperextension during breathing can cause the legs and hips to drop lower in the water causing increased form drag. When the head rise and neck movement are reduced, disruptions to streamlining and form drag are minimized.
is passive when a swimmers' pure size contributes to the resistance. It is active and disadvantageous when the swimmer's position in the water is not fully streamlined (e.g., swimming with a head-up position in backstroke which causes the hips to drop deeper in the water than the cross-sectional area presented by the shoulders and chest area alone; looking directly ahead in breaststroke which causes the hips to drop and the general body angle to be tilted rather than being as flat as possible). If a swimmer's action or swimming "posture" deliberately creates an increased cross-sectional area then progress through the water will be slowed more than it should be. In that case, the incorrect swimming alignment produces extra resistance which is actively created although it could be reduced. Form drag increases in seriousness as a swimmer's speed increases.

Form drag can be lessened by accentuating streamlining at every opportunity (i.e., the swimmer has to create the thinnest and straightest from while going through the water). A general concept for most strokes is to have the shoulder/chest area create a gap in the water and the hips and legs follow through that space. That usually translates into swimming as flat as possible. Even the new breaststroke kick is designed to reduce the dropping of the knees that was a noted feature of the old action. When a breaststroker kicks and at the same time allows the hips to rise, that elevates the knees and reduces their contribution to form drag as well as producing a propelling force that is more horizontal and beneficial than the old, slightly downward kick. Most new advances in technique have aimed at maximizing streamlining, that is, reducing form drag. Kolmogorov and Dupliseheva (15) showed that swimmers of similar body size (height and weight) can have drastically different active drag values. Two females differed in active drag by 15 N while swimming at the same velocity. Two equally weighted males with a 2 cm difference in height differed by 34 N. In the male swimmers, the top swimming velocities also differed. The swimmer with higher drag was 0.15 m/s slower. These data show that streamlining and proper body positioning may be a significant way to increase swimming speed by decreasing resistance. The streamlined position of Kieren Perkins, when compared to that of Joerg Hoffman, could account for some portion of their performance difference (see Figure 15). The peak in Hoffman's propulsive force was approximately 100 N for the left and 75 N for the right hand. Those values were higher than those of Perkins who demonstrated forces of 51 N or less (4). Thus, Perkins, the faster swimmer, developed less force. His better streamlining could be promoted as an obvious contributor to his superiority.

KIEREN PERKINS

Good Streamlining

JOERG HOFFMAN

Poor Streamlining

Figure 15. A comparison of the streamline positions of Kieren Perkins (at the 1992 Olympic Games) and Joerg Hoffman (at the 1991 World Championships). Perkins' superior streamlining may account for much of his superiority over his arch rival Hoffman.
Wave Drag

Wave drag occurs when a swimmer creates waves, wakes, and turbulence and is often termed active drag. Since waves carry energy, the source of that energy comes from the swimmer. Energy that could be applied to productive force is lost by unnecessary wave production. Although body position in the water has been described as contributing to form drag by increasing frontal resistance, it also contributes to wave drag by increasing following turbulence (usually termed "eddy resistance"). Figure 16 illustrates the major features concerning wave drag.

Examples of wave production are; accentuated vertical movements (e.g., "flying" out of the water in butterfly, lifting the head when breathing in crawl stroke), lateral movements (e.g., hip sway in backstroke that results from the hand entry being placed behind the head; breathing backwards in crawl stroke that produces a hip movement and sideways kick), and any action that is not in a longitudinal horizontal direction. Any bouncing or jerkiness in a swimmer's style also creates wave drag. Because of the human anatomy, it is not possible to remove all movements outside of the direct horizontal-longitudinal plane, but when they are exaggerated, wave drag becomes a major problem.

This is the worst form of drag because it increases as the cube of swimming velocity. The faster a swimmer goes, its contribution to resistance increases dramatically. This type of drag is one over which a swimmer has a great degree of control. Usually, increases in wave drag are also accompanied by increases in form drag which makes their effects on propulsion particularly noticeable.

Wave drag can be minimized by reducing unnecessary vertical and lateral movements. Attempts to over-extend forward and backward that produce even the slightest bending of the body up or down are not worthy of adoption because of the detrimental consequences of the wave drag that is created. Similarly, attempts to swim over the water in crawl stroke and butterfly also generates large vertical forces and unnecessary movements that create accentuated wave drag.

There are some beneficial vertical movements that can contribute to forward propulsion. The wave action that travels down the body in modern breaststroke and butterfly is helpful. However, if that action is exaggerated to the point where the undulation is too large and the wave is not as fast as the swimmer's velocity, then it will actually slow the swimmer more than if no wave action was attempted at all.

The effects of slowing are different for each form of drag. If a swimmer doubled the speed of swimming, frictional drag would be twice as much as at the original speed, form drag would be four times as much, and wave drag would be eight times as much. It can be seen that these features of swimming efficiency become increasingly more important as a swimmer attempts to increase speed. There comes a time when, because of the wave and form drag that are involved in a swimmer's
WAVE DRAG

WHEN A SWIMMER CREATES WAVES OR WAKES, THE ENERGY OF THE WAVES ORIGINATES WITH THE SWIMMER.

VERTICAL AND LATERAL MOVEMENTS DISSIPATE ENERGY IN GREAT AMOUNTS.

RELATIONSHIP OF WAVE DRAG TO SPEED IN WATER.

Cubic relationship.

Figure 16. Features concerning wave drag in swimmers. Actions which shift large amounts of water transfer much energy to that water instead of to propulsion. Examples of three common movements that increase wave drag in swimmers are illustrated. A: excessive diving at the butterfly entry; B: excessive reaching across behind the head at the backstroke entry which causes the hips to move laterally; C1: raising the head excessively to breath in crawl stroke produces an exaggerated kick; and C2: lowering the excessively raised head back into the water moves a large volume of water. These actions also contribute to increased form drag which makes them doubly troublesome.
technique, any attempt to swim faster would consume so much energy to overcome the increased drag functions, that the energy required could not be mustered.

Although the three forms of drag have been explained separately, in the dynamic actions of swimming one unnecessary action could cause detrimental increases in each form of resistance. For example, if a swimmer exaggerated the head and shoulder movement in butterfly by diving unnecessarily at the entry, the following would likely occur: (a) frictional drag would increase because of the complete covering of the upper body and back of the head; (b) form drag would increase because of the increased departure from a streamlined alignment caused by excessive hip flexion; and (c) wave drag would be increased because of the excessive displacement of water. Thus, when considering resistances that result from swimming actions it is prudent to consider if the three forms of drag have been affected rather than just one or two.

It is because of the increasing importance of drag as speeds increase that unnecessary movements should be eliminated from swimmers’ techniques. Streamlining (reducing all forms of drag on non-propulsive body segments) is relatively simple in technique modification that will also affect how easily a swimmer slips through the water. Streamlining reduces both form and wave drag. Shaving and wearing a technically efficient suit also are easy actions that will reduce frictional drag and consequently, will assist in speeding up swimmers.

Practical Implications

For every technique change that is attempted in swimmers, its effect on drag has to be considered. If drag is increased, then it most likely will not be of advantage to change a swimmer’s technique.

These components of resistance cannot be ignored by a caring coach. They slow swimmers. If a swimmer attempts to go faster by producing more effort, and that effort alters technique to produce greater amounts of unproductive movements, then the added resistance caused by those movements may offset any potential speed benefits generated by the extra effort.

The technique of swimming fast must be efficient and produce the least resistance possible. Attention to drag factors will contribute to propelling efficiency and will make swimming fast a lot easier. However, it may be necessary to compromise and tolerate some resistive drag forces. Stroke length is one of the most significant factors associated with sprint swimming success (14). If a long stroke facilitates increased propulsive forces, even though increased resistance is developed on the way to obtaining the greater length, then as long as the net gain is positive (i.e., propulsion developed is greater than resistance developed) the implied inefficiency could be tolerated.

The relationship of increases in resistance to increases in speed creates a hierarchy of coaching preferences. 1. Streamlining and the minimization of drag are paramount.

2. Actions which cause vertical movements, particularly of the head, shoulders, and hips, should be minimized and, where possible, eliminated.

3. Actions which cause lateral movements, particularly of the head, shoulders, and hips, should be eliminated.

4. Technique alterations and actions should only be those which do not upset the position and actions which minimize drag.

5. Technique changes should not be made or modified if they produce a negative alteration in a swimmer’s position and postural control in the water.

Summary

This discussion has attempted to assess the development of thinking and research over the past 25 years for understanding the basic properties of force production in swimming strokes. It has described the limitations and deficiencies of Bernoulli’s Principle for being the basic explanation for propulsive forces. Bernoulli’s Principle is simply too limited and inappropriate for accounting for observed and measured phenomena in competitive swimming strokes. Evidence reveals that lift forces are minor and rarely in a substantially beneficial direction in propulsive phases of the crawl, back, and butterfly strokes.

In breaststroke, both forces are recorded in the inward and outward sculling phase of the stroke. However, drag forces generally are not in a facilitatory direction and so forward propulsion results mainly from lift created by an exaggerated angle of attack (when compared to those exhibited in crawl, back, and butterfly strokes), and a large canceling of effect of the mostly symmetrical drag forces. The dominance and importance of lift forces in breaststroke is not a justification for promoting Bernoulli’s Principle as the foundational reason for propulsion.

Drag forces are dominant and in a facilitating direction during propulsion in crawl, back, and butterfly strokes. The extent of their importance is markedly more than any lift force contribution.

In breaststroke, drag forces created by both arms can be largely ignored because the direction of the outward and inward movements makes one cancel out the other. Thus, the emphasis should be on developing lift which will require a greater angle of attack in the hands and forearms than occurs in the other strokes.

Several practical considerations were drawn from the assertions made to date. They will require a change in teaching/coaching emphasis of many practitioners who have promoted an exaggeration of the S-shaped pull,
that is, they believe that large sideways movements are beneficial for propulsion. A greater emphasis should be placed on advising swimmers to focus on the role of the forearm in propulsion, particularly at higher speeds.

Three forms of resistance were proposed for consideration. They have practical implications for coaches. Frictional drag can be reduced by shaving and wearing a suit with a fabric that has a low coefficient of resistance. Form drag can be minimized by maintaining streamlined positions during the entirety of all strokes. Wave drag can be minimized by removing any unnecessary vertical and all lateral and exaggerated movements. Attention to the details of drag reduction is most important when speed of swimming is emphasized.

The production of force is important. However, resistance increases at a much greater rate than changes in speed due to propulsive forces. Thus, it is advocated that swimming actions first should be oriented to minimizing resistance, and second, to developing propulsion as long as positions for minimal resistance are maintained.

This paper has called for a change in entrenched thinking with regard to propulsive and resistive forces. When that change is made and its importance introduced into coaching the progression of swimmers' performances should improve.

References
Differences in Peak Blood Lactate Concentration in Long Course Versus Short Course Swimming

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Abstract

This study examined differences in peak blood lactate (LAC) levels following a 200 meter freestyle swim in both a 50 meter long course (LC) and a 25 yard short course (SC) pool. Twenty male and female collegiate swimmers were randomly assigned to two groups. Group one performed a maximal effort 200 meter freestyle swim SC followed two days later by a swim of identical length LC. The second group underwent the same swim challenges in reverse order. Performance time (PT), pre- and post-exercise heart rate (HR) and LAC levels were obtained for each 200 meter swim. To control for differences in post-exercise LAC attributable to different baseline levels, △LAC (post LAC - pre LAC) was also determined. No significant effect of pool length on PT or HR was observed. However, peak LAC was significantly higher LC (10.76 ± 3.14 mM/L) than SC (9.27 ± 3.11 mM/L) (p<.001) irrespective of swimming order. Likewise, the △LAC values were 14.9% higher LC than SC (p<.01). These findings suggest that when swimming at comparable intensities and distances in pools of different length, a LC pool will produce higher peak lactate levels than a SC pool. We conclude that pool length must be taken into consideration when using lactate levels to determine optimal training intensities.

Introduction

During the past decade measurement of blood lactic acid concentration has been used to accurately evaluate and predict performance during submaximal and maximal swimming. These measurements have also aided in the design of training programs for elite swimmers. The lactic acid concentrations in the blood are commonly used to establish the optimal training intensity by determining the relationship among blood lactate, swimming intensity, and heart rate (HR) in prolonged and interval-type training. This relationship allows coaches to objectively control the intensity of swimming during training by targeting energy systems necessary to optimize performance in swim events of differing intensity and duration (7).

The difference in swim performance between races of identical distance performed in a 25 meter or 25 yard short course (SC) pool and races in a 50 meter long course (LC) pool is well-appreciated in swimming science. Faster performance times are commonly observed during events performed in SC pools, an advantage usually associated with the greater number of turns necessary to complete the same competition distance. The greater number of turns offers swimmers several performance advantages, including increased propulsion from each turn and a period of relative inactivity during which moderate exercise recuperation results. Both of these factors may allow for advantageous transitory reduction of lactate acid concentrations in the blood and muscle.

It has been suggested by Telford et al. (8) that a relationship exists between different pool lengths and changes in blood lactate levels sustained during swimming. These authors measured post-competition blood lactate levels in elite Australian swimmers during 25 and 50 meter pool competitions in successive weeks, and observed that racing in the 50 meter pool produced higher blood lactic acid concentration than in the 25
meter pool. The average maximal blood lactic acid concentration for males and females was 3.8 mM/L ± 0.6 mM/L (Mean ± S.D.) greater in a 50 meter than a 25 meter length pool. Unfortunately, the investigators also acknowledged a failure to control for several factors which might have influenced the blood lactate concentration. These included motivational factors which may have differed in the LC and SC competitions, tapering which occurred in the week between the two competitions, and non-randomization of sampling. As measurement of blood lactate concentration during swimming may ultimately influence choices of exercise training strategies, adaptive responses to training, and competition performance, the purpose of this study is to compare blood lactate responses following a 200 meter swim at maximal pace in a 50 meter LC pool with those of a 200 meter swim in a 25 yard SC pool.

**Methods**

Twenty swimmers (13 male, 7 females) from the University of Miami swim team volunteered to serve as subjects for this experiment. All subjects were between the ages of 18 and 23 years (19.6 ± 1.5) and had participated in at least three years of competitive swimming prior to the study. The subjects had undergone intensive training for five months prior to the study, swimming an average of 7500 meters per day, six days weekly. Before testing all subjects were acquainted with the study protocol and consented to participate in accordance with the guidelines of the Medical Sciences Subcommittee for the Protection of Human Subjects.

The twenty swimmers were randomly assigned to one of two groups. Group one swam a maximal pace 200 meter freestyle in the short course pool, followed two days later by a maximal pace 200 meter freestyle in the long course pool. Group two performed the same tests but in reverse order. The long course pool was 50 meters in length, and therefore, a 200 meter swim consisted of swimming four complete lengths. The short course pool was 25 yards in length, and therefore, the 200 meters consisted of swimming 218.7 yards—or eight complete lengths—plus an additional 18.7 yards.

Prior to the maximal pace swim, subjects performed a 23 minute low intensity warm-up which was followed by a five minute rest period. Blood sampling for lactate determination commenced at minute three of the rest period and the pre-exercise heart rate (HR) was taken one minute later. Following the five minute rest period, participants swam a timed maximal pace 200 meter freestyle. The post-exercise HR was taken immediately following the completion of the swim. The subjects then exited the pool and walked approximately 14 meters to the sampling area where they were seated. Three, five and eight minutes into their passive recovery, a sample of free flow mixed capillary blood was collected by a finger stick. The highest value obtained from these samples was used as the peak lactate. Additionally, to control for the influence of pre-exercise LAC on peak LAC, LAC values were expressed as the difference between the pre-swimming and post-swimming measurements (ΔLAC).

Blood samples (30-50uL) were collected in heparinized capillary tubes prepared with: 1) fluoride to inhibit glycolysis, and 2) nitrite to convert hemoglobin to the met-hemoglobin form so as to prevent erythrocyte oxygen uptake or egress. Lactate analysis was carried out within 60 minutes of blood sampling using an Analox LM3 Lactate Analyzer (P.K. Morgan Instruments Incorporation).

The swimming intensity was evaluated by two methods: 1) the exercise heart rate following completion of the swimming trials at the two pool lengths, and 2) the time necessary to complete the 200 meter freestyle swim in the LC and SC pools. Due to the additional propulsion from the extra turns in the 25 yard pool, a 2.5% conversion factor was used to match long course and short course times. This conversion factor was calculated in the following manner: A 2.0% conversion factor is used by the Quebec Swimming Federation to correct standards from a 25 meter to a 50 meter pool. This equals 0.5% for each of the additional 4 turns. Assuming a linear relationship between the number of additional turns and an increase in performance time, the five additional turns needed when swimming 200 meters in a 25 yard pool would require a 2.5% conversion factor.

Pair Students t-tests were used to compare the following dependent variables measured for both the SC and LC pool testing: 1) pre-exercise lactate, 2) peak lactate, 3) △lactate, 4) pre-exercise heart rate, 5) post-exercise heart rate, 6) time to complete the 200 meters freestyle and 7) time to complete 200 meters freestyle corrected for the number of turns. T-tests for independent samples of equal size were conducted on the dependent variables to compare differences between groups. Statistical significance was accepted at the p<0.05 level.

**Results**

Baseline measures, physiological response to swim testing, and timed outcomes of testing are shown in Table 1. No significant differences were observed for any dependent measure when groups were stratified by order of swim. Thus, the following analyses reflect the collapse of the two "order-of-swim" groups into single groups, each representing testing in either the long or short course pool.

No significant effect of pool length was observed for pre-exercise heart rate and lactate concentration. As well, the post-swimming heart rates did not differ between groups. Conversely, a significant effect of pool length
Table 1. Physiological variables of subjects (n = 20)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Short course</th>
<th>Long course</th>
<th>% change</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-exercise lactate (mM)</td>
<td>1.75 ± 0.7</td>
<td>1.91 ± 0.6</td>
<td>8.4</td>
<td>1.02</td>
</tr>
<tr>
<td>Peak lactate (mM)</td>
<td>9.27 ± 3.1</td>
<td>10.76 ± 3.1</td>
<td>13.8</td>
<td>4.17***</td>
</tr>
<tr>
<td>Δ lactate (mM)</td>
<td>7.48 ± 3.3</td>
<td>8.84 ± 3.1</td>
<td>14.9</td>
<td>3.82**</td>
</tr>
<tr>
<td>Pre-exercise heart rate</td>
<td>84.4 ± 10.8</td>
<td>86.2 ± 11.0</td>
<td>2.1</td>
<td>0.65</td>
</tr>
<tr>
<td>rate (beats/min.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-exercise heart rate</td>
<td>161.4 ± 9.2</td>
<td>161.6 ± 9.5</td>
<td>0.1</td>
<td>0.16</td>
</tr>
<tr>
<td>rate (beats/min.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time for 200 meters</td>
<td>128.4 ± 10.7</td>
<td>132.3 ± 9.1</td>
<td>3.0</td>
<td>7.45***</td>
</tr>
<tr>
<td>(seconds)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time for 200 meters</td>
<td>131.7 ± 10.9</td>
<td>132.3 ± 9.1</td>
<td>0.6</td>
<td>1.06</td>
</tr>
<tr>
<td>(2.5%) converted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean ± S.D.
* p < .05
** p < .01
*** p < .001

was observed for the PT, with the faster times favoring the shorter pool (p < 0.001). This significant effect was nullified when the 2.5% conversion factor was used to correct for the added turns performed in the short course pool.

Peak lactate concentrations were significantly higher following the long course swim (10.76 ± 3.14 mM) than the short course swim (9.27 ± 3.11 mM) (p < .001). Moreover, Δlactate values were significantly higher following the swim in the long course pool (8.84 ± 3.14 mM) than the short course pool (7.48 ± 3.32 mM) (p < .01).

Discussion

The present study reports that peak blood lactate and Δlactate concentration for a 200 meter swim are greater when performed in a LC pool. One of the important observations of this study is that lactate concentration differed under the two test conditions despite the well-matched intensities of swimming during the long and short course trials. Thus, the lactate concentration differed, although neither HR nor the corrected PT for the events differed. These findings differ from the longstanding exercise dictum and previous reports of Arabas et al., (1) Noble et al., (6) and Torma and Szekely (9), that higher exercise intensities produce greater accumulation of lactic acid. It is unlikely, however, that exercise intensity influenced our results, as both post-exercise HR and time to complete the event were not significantly different when the two pool lengths were compared. Mean post-exercise HR were identical for both swims, and time to complete the 200 meters freestyle was also not significantly different in both pool lengths after the 2.5% conversion was used to correct the advantage of the added turns.

The observation that intensity-matched swim challenges produced different lactate-concentrations in the same swimmers suggests that the number of turns may play an important role in regulating physiological response to swim challenges. Maglischo (5) has reported that swimmers spend 2 to 3 seconds on each pool length turning and gliding. Thus, for a 200 yard freestyle event performed in a short course pool, an average of 33% of the race is spent turning, with turns defined as the time from cessation of normal stroking action until the resumption of normal stroking action (2). As swimming in a long course pool requires four fewer turns than a short course pool, 16% less of the event time would be spent turning. Thus, the difference in lactate concentration between the two pool lengths is presumably related to the doubled frequency of turns in the short course pool which provides relative inactivity for the arms and shoulders.

The findings of this study suggest that the time spent during relative inactivity in swim turns ought not be trivialized. The period used for the turn and the glide represent a time in which muscles used for propulsion experience a short period of relative inactivity. The recovery experienced during this inactivity may result in decreased muscle lactate production, increased rates of clearance of lactate from the sarcoplasm of these muscles to the extracellular fluid, and a possible increased uptake of lactate by less metabolically active muscles. Increased utilization of lactate by inactive muscles during exercise has been reported by Brooks (2), and it has been observed by Cumming and co-workers that serum lactate concentrations are affected by their rate of metabolism in the liver and heart, as well as working and non-working muscles. (3)

Practical Application

These findings call attention to coaches, trainers, and physiologists that lactate measurements used to assess swim performance and compute training intensities in a SC pool ought not be used for a LC pool. Thus, teams that use lactate measurements to design optimal training intensities for their swimmers must also establish individualized profiles for the different pool lengths so as to avoid training intensity errors.

On first examination, it might appear that swimmers who train in LC but compete in SC pools might be advantaged, although this is not the case. First, the findings of this study support a specificity of training in which preparation for a distinctive event heightens performance selectively related to that event. Second, the
findings of this study fail to take into consideration that the number of strokes per pool length or rate of stroke turnover may differ for the same swimmer when competing in pools of differing length. Thus, training in a pool unlike their competition pool may rob them of the preparation necessary to adapt to higher muscle lactate levels generated in LC pools, or, deny them practice for the higher number of turns necessary for the same event in SC pools. Moreover, inefficient turns may attenuate the recuperation time we hypothesize accounts for the lower lactate measured in the SC pool swimmers from this study. Third, there is no experimental evidence to confirm that higher tolerance to lactate acquired through training in LC pools benefits the swimmer in short course competitions. Conversely, swimmers trained in SC pools are at a clear disadvantage when competing in long course pools, as they may be unaccustomed to higher muscle and systemic lactate levels generated in LC pools and would be more susceptible to lactate-induced muscle fatigue.

Additional research is needed to determine if the results of this study are replicated during swimming events involving other distances and strokes, or, during submaximal work intensities. In particular, the use of \( \Delta \) lactate as a predictor of work intensity during submaximal work requires validation. The \( \Delta \) lactates should also be compared for 200 meter freestyle swims in a 25 meter and 50 meter pools, as the extra turn used to correct for the shorter 25 yard pool in this study may have disproportionately affected the \( \Delta \) lactate concentration. Additionally, the finding of large intra-individual differences in \( \Delta \) lactate concentration requires additional research scrutiny. We observed, without consistent or identifiable trend, that some subjects had much higher \( \Delta \) lactate values in the long course pool while others did not. It is not known whether these observations were attributable to individual differences in lactate metabolism, or contrasting mechanical skill in executing their swim turns.

We conclude that pool length influences lactate and \( \Delta \) lactate concentration when an event is performed at constant intensity and distance. The pool length must be taken into consideration when comparing swim performances in pools of different length, and when planning training strategies based upon targeting of specific energy systems and lactate concentrations.

References
Carbohydrate Ingestion During Competitive Swimming Training

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Abstract

To evaluate the possible effect of carbohydrate ingestion on maintenance of blood glucose concentration and performance, 9 male university swimmers performed a 6,500 yd swim training session once while ingesting placebo every 30 min and once while ingesting a carbohydrate beverage every 30 min. Blood samples were obtained before exercise and immediately before every carbohydrate/placebo feeding. Performance was evaluated at the end of the training session as average time for a set of ten 100 yd freestyle swims on a 1 min 20 sec interval. Blood samples were analyzed for glucose and lactate concentrations. There was not a significant drop in the group mean glucose concentration during the placebo trial (5.1 ± 0.8 mM pre-exercise vs 4.8 ± 0.3 mM immediately before 10 x 100 yd swim) and although carbohydrate feedings tended to elevate the blood glucose concentrations throughout the training session, there was not a significant group mean difference in glucose concentrations between placebo and carbohydrate trials. Group means for performance time on the 10 x 100 set were also not significantly different between placebo and carbohydrate trials. However, in 2 of the subjects, blood glucose concentration dropped dramatically in the placebo trial. This decline in blood glucose concentrations was completely prevented by the carbohydrate feedings and performance was improved by 1.1 sec for one of the subjects and by 1.3 sec for the other. It is concluded that carbohydrate feedings during a long swimming training session may help prevent a decline in blood glucose concentrations and aid performance in the latter part of training only in those swimmers who normally experience lowered blood glucose during training.

Introduction

The daily training schedule of competitive swimmers places extraordinary physiological demands on the individual. Swimmers often train 2-3 hr/session, twice per day, 6 days/wk. The majority of this training involves repeated bouts of moderate-intensity exercise (interval training). Because of the large volume of training swimmers typically use, most of the training is performed at submaximal intensities and can be described as aerobic or endurance training.

Several studies have shown that carbohydrate feedings during endurance exercise can help prevent a decline in blood glucose and improve performance, especially during the latter half of the exercise (3,5,6). By feeding subjects 1 g/kg glucose polymer after the initial 10 min period of exercise and then 0.6 g/kg glucose polymer every 30 min thereafter, Coggan and Coyle (1) demonstrated significantly elevated blood glucose concentrations and increased endurance time when compared with placebo. Davis et al. (7) examined the effect of feeding carbohydrate on the performance of an exercise test performed after 2 hr of continuous cycling at 75% of VO2max. In this study, subjects were able to perform the assigned task (time to complete 2700 pedal revolutions) significantly faster with carbohydrate ingestion (31 min) than with placebo ingestion (34 min). Tsintzas et al. (10) tested the effect of carbohydrate feedings every 5 km during a 30 km running time trial. When given the carbohydrate feedings, the runners performed the 30 km trial approximately 3 min faster than when on placebo. Furthermore, all of the performance improvement in the carbohydrate trial was observed during the final 5 km of the race.

Collectively, these studies suggest that frequent carbohydrate feedings during exercise can prevent a drop in blood glucose during endurance exercise, delay the onset of fatigue, and result in improved performance at the end of the exercise. Because both duration and intensity of competitive swimming training are similar to these early studies that show beneficial effects of carbohydrate feedings, providing a carbohydrate beverage to swimmers during long practices may improve their perform-
ance during the latter part of the training session. Although performance in practice is not measured against the competition, decreased fatigue in the latter part of practice sessions may help the swimmer gain greater adaptations to the training which could ultimately improve their competitive performances. It was therefore the purpose of this study to evaluate the effect of carbohydrate feedings during a typical swim training session on blood glucose homeostasis and performance of the final training bout during the practice.

Methods
Nine male volunteers from a NCAA Division I swimming team participated in this study. The study design was reviewed and approved by the institution’s Human Subjects Review Committee. All procedures and pertinent risks were explained to the subjects before they gave written consent to participate. Subject characteristics are shown in Table 1.

Table 1. Subject characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>20 ± 0</td>
</tr>
<tr>
<td>Body Weight (kg)</td>
<td>82.1 ± 3.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>183 ± 2.1</td>
</tr>
<tr>
<td>VO₂ peak (ml/kg/min)</td>
<td>3.67 ± 0.15</td>
</tr>
</tbody>
</table>

Preliminary Testing
Within the 2 wk prior to the study, subjects were tested to determine VO₂ peak using a maximal 400 yd swim as described by Costill et al (4). Briefly, this test involved a 400 yd front crawl swim in which the swimmers were asked to perform the swim as fast as possible using relatively even pacing. Immediately after the swimmer finished the swim, expired air was collected for 20 sec in non-diffusible gas bags for subsequent analyses of expired volume (Parkinson-Cowan gas meter), percentage oxygen (Applied Electrochemistry SA-3 Oxygen Analyzer), and percentage CO₂ (Beckman LB-2 CO₂ Analyzer). VO₂ was calculated using standard equations and the correction factor for 20 sec recovery samples was applied (4).

For 2 days before the first experimental trial, each subject recorded the types and amounts foods and beverages consumed. The subjects were asked to choose easily reproduced meals, and were instructed to duplicate this 2-day diet prior to the next trial. These diet records were subsequently analyzed for energy content and macro-nutrient contents using a commercially available computer-based diet analysis program (FoodComp, ISU). Before each subjects’ second trial, his diet records were returned to him so that he could replicate the diet. Summary data from the subjects’ diets are shown in Table 2.

Table 2. Composition of the subjects’ (n=9) diet for 2 days prior to each trial.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Intake (kcal/day)</td>
<td>3967 ± 315</td>
</tr>
<tr>
<td>Protein (g/day)</td>
<td>133 ± 14</td>
</tr>
<tr>
<td>Fat (g/day)</td>
<td>120 ± 10</td>
</tr>
<tr>
<td>Carbohydrate (g/day)</td>
<td>609 ± 59</td>
</tr>
<tr>
<td>% Protein</td>
<td>14 ± 1</td>
</tr>
<tr>
<td>% Fat</td>
<td>27 ± 2</td>
</tr>
<tr>
<td>% Carbohydrate</td>
<td>58 ± 2</td>
</tr>
</tbody>
</table>

Figure 1. Components of the training session, protocol for blood sampling, and ingestion of experimental solutions.
Experimental Testing

Each subject performed two experimental trials in the morning after an overnight fast. The trials were conducted 7 days apart using a cross-over double-blind design. Both trials consisted of a 6,500 yd swim training session. This training session was designed by the team’s coach to be typical of a 2 hr practice session normally performed by the swimmers. The structure of the training session is shown in Figure 1. The final 1000 yd of the practice consisted of 10 repetitions of 100 yd leaving every 1 min 20 sec that served as the performance trial. In this interval set, subjects were asked to achieve the fastest possible average time over the entire 10 repetitions. Times were recorded by two observers to the nearest 0.1 sec and average time was computed for the first 5 repetitions, the second 5 repetitions, and for the whole set of 10 repetitions.

The carbohydrate feeding schedule was that of Coggan and Coyle (1) and included 1 g/kg body weight carbohydrate (Polycose; Ross Laboratories) dissolved in a 50% solution given after 10 min of exercise and 0.6 g/kg in a 20% solution every 30 min thereafter. The placebo was given in the same volume as the carbohydrate drink over the same dose schedule. The placebo was an artificially sweetened (Nutra-Sweet) and flavored drink ingested in a volume equal to that in the carbohydrate feeding trial.

During the two experimental trials, immediate post-exercise heart rate was measured at 10, 40, 55, 70, 85 min, after the first 5 repetitions of the performance trial, and at the end of the performance trial. Fingertip blood samples (20 ul) were obtained prior to starting the training session, prior to each feeding, and immediately after the performance trial. Blood was immediately added to 50 ul lysing reagent (sodium fluoride and Triton X-100) for analysis of blood glucose and lactate concentrations. These analyses were performed on a YSI Model 2800 Glucose-Lactate Analyzer that was calibrated with known standards after every 5 determinations. To eliminate possible interference from the lysing reagent, sodium fluoride and Triton X-100 were added to the YSI buffer. Interassay variability was eliminated by analyzing all samples from each subject in the same assay run.

All data were analyzed for significant differences between the carbohydrate (CHO) trial and placebo (PLA) trial using two-way ANOVA for repeated measures. When a significant F ratio (p < 0.05) was obtained, a Newman-Keuls multiple range test was used to locate the significantly different means.

Results

In both experimental trials heart rate gradually increased through the training session, reaching the highest level at the end of the performance trial. However, there were no significant differences between the CHO and PLA trials at any point during the training session. These data are shown in Figure 2.

![Figure 2. Mean ± SEM heart rate responses at various times during the training session and performance trial.](image)

During the PLA trial, blood glucose concentration remained fairly stable throughout the first 100 minutes of the training session (Fig. 3). During the performance trial, however, blood glucose concentration increased

![Figure 3. Mean ± SEM blood glucose concentrations throughout training session and performance trial when given placebo (PLA) and carbohydrate feeding (CHO).](image)
significantly by the end of the exercise. Carbohydrate feedings resulted in higher blood glucose concentrations than PLA during the training session and the performance trial but none of these differences reached statistical significance. Blood lactate concentration was significantly elevated over the pre-exercise level from the 70 min time period onward in both trials (Fig. 4). As expected, blood lactate concentrations showed a further significant increase during the performance trial. Despite these dramatic changes in blood lactate concentrations during the training session and performance trial, there were no significant differences between the CHO and PLA trials.

![Figure 4. Mean ± SEM blood lactate concentrations throughout training session and performance trial when given placebo (PLA) and carbohydrate feeding (CHO).](image)

The subjects were able to average 59.1 ± 1.0 sec per 100 yd repetition during the performance trial in which placebo was ingested (Fig. 5). In the CHO trial, the average time per 100 yd was 59.9 ± 0.9 sec. These differences were not statistically significant. Average times for the first five 100 yd repetitions were also not different, nor were average times for the second five repetitions different between CHO and PLA trials.

It should be mentioned that only 2 of our subjects experienced a drop in blood glucose concentration during the placebo trial. In subject #1 blood glucose dropped from 4.3 mM pre-exercise to 2.6 mM at 100 min into the training session (at the end of the set preceding the performance trial). During his 10 x 100 performance trial, his average time was 64.3 sec. Ingestion of the carbohydrate prevented the decline in blood glucose (0.2 mM drop from pre-exercise to 100 min) and his average time for the performance trial was 63.0 sec. In subject #2 blood glucose dropped from 5.6 mM pre-exercise to 3.7 mM at 100 min in the placebo trial. His average time in the performance trial was 58.4 sec. During the CHO trial his blood glucose concentration increased from pre-exercise (5.7 mM) to 100 min (7.2 mM) and his subsequent performance average was 1.1 sec faster (57.3 sec) than in the placebo.

![Figure 5. Mean ± SEM swim time (sec) per 100 yd during first half, second half, and for entire set of 10 x 100 yd swim performance trial when fed placebo (PLA) and carbohydrate (CHO).](image)

**Discussion**

The major finding of this study was that even when fed a placebo, this group of subjects did not experience a declining blood glucose concentration during the course of a 2 hr competitive swim training session. Consequently, frequent ingestion of a carbohydrate beverage during the training session provided no benefit in helping to maintain blood glucose concentration.

The lack of a decline in blood glucose during the placebo trial does not agree with a number of earlier studies (1,2,5,8,10). There are several possible explanations for this lack of agreement including differences in exercise intensity; the fact that during a swim training bout, blood samples can only be taken after an exercise bout has been stopped; and that only some individuals may experience a drop in blood glucose during endurance exercise (5). In the present study and in competitive swim training in general, the swimmers perform intermittent exercise (interval training). Because blood
samples cannot be taken while the swimmer is exercising, it is possible that enough time elapses between the completion of a swim and blood sampling for blood glucose concentrations to rise. This immediate post-exercise rise in blood glucose concentration results from the combined effect of continued glucose output from the liver coupled with the sudden decrease in muscle glucose uptake. Consequently, blood glucose concentrations rapidly rise and if the sample is obtained during this time, any possible glucose-lowering effects of the prior exercise may be masked.

There are other studies that have not shown a decline in blood glucose concentration during endurance exercise (5,9,11). It is possible that only a portion of the exercising population will experience declining blood glucose in endurance exercise and that the random sampling of subjects employed by investigators occasionally results in inadvertent recruitment of subjects that tend to or tend not to experience the decline in blood glucose. For example, Coyle et al (5) reported that 7 out of 10 of his subjects experienced a decrease in blood glucose during 90 min of cycling at 74% of VO2max when placebo was ingested throughout the exercise. In the carbohydrate feeding trial, performance was improved in only these 7 subjects. In the present study, 2 of the 9 subjects experienced a drop in blood glucose concentration during the placebo trial. In agreement with Coyle et al. (5), the decline in blood glucose concentrations of these subjects was prevented by the ingestion of carbohydrate and their performance on the 10 x 100 yd swim boat was improved. These data along with Coyle et al. (5) imply that carbohydrate feedings during exercise may be beneficial only in those people who normally experience declining blood glucose during endurance exercise. Further research should be conducted to help identify those swimmers who are most likely to experience a drop in blood glucose concentration during training and to identify physiological, metabolic, and/or dietary factors that may affect this response.

**Practical Applications**

The abundance of scientific and lay literature suggesting carbohydrate feedings during endurance exercise may lead some swimming coaches to feel it necessary to provide swimmers with a carbohydrate-containing beverage during training sessions. However, the present results as well as those of others suggest that not all athletes may benefit from frequent carbohydrate feedings during the exercise. In those athletes that normally experience a drop in blood glucose during training, however, frequent ingestion (every 20-30 min) may help prevent this decline and result in improved ability to perform strenuous training bouts that occur late in a training session. Unless coaches have access to a blood glucose analyzer, however, it is difficult for them to know which of their swimmers experience a drop in blood glucose during training. As an alternative to measurement of blood glucose concentrations during training, coaches can encourage carbohydrate feedings in training for all their swimmers or just for those who seem to experience undue fatigue and impaired performance towards the end of training sessions.

Several of the swimmers in the present study noted that the carbohydrate feeding schedule we used caused them to feel "bloating" especially during the latter third of the training. This was not expected because in the prior studies using cyclists and/or runners, discomfort was not mentioned as a potential side effect of the feedings. Nevertheless, it would be appropriate for coaches to decrease either the volume of solution consumed or the concentration for those swimmers who experience discomfort.

In choosing an appropriate carbohydrate beverage, coaches can try the different commercial fluid/carbohydrate beverages or duplicate the feeding protocol used in the present study which was taken from Coggan and Coyle, et al (1). Table 3 contains the information to make the two solutions used in the present study and to determine the volume of these solutions for swimmers to consume.

<table>
<thead>
<tr>
<th>Body Weight (kg)</th>
<th>Solution* (g/100 ml)</th>
<th>Dose (g/kg)</th>
<th>Volume (ml)</th>
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<tbody>
<tr>
<td>45</td>
<td>20</td>
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<td>225</td>
</tr>
<tr>
<td></td>
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<td>50</td>
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<td>0.6</td>
<td>250</td>
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<td></td>
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<td>100</td>
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<td>55</td>
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<td>0.6</td>
<td>275</td>
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<tr>
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<td>85</td>
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<td></td>
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<td>1</td>
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<td>90</td>
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<td>0.6</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1</td>
<td>180</td>
</tr>
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</table>

*To make 1 liter of the 20% solution, dissolve 200 g Polycose® in water in a final volume of 1 liter. To make 1 liter of the 50% solution, dissolve 300 g Polycose® in water in a final volume of 1 liter.
References
The Relationship Between Physiological Variables From a Swim Bench Ramp Test and Middle-Distance Swimming Performance

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Bedford, England
MK40 2BZ.

Abstract
The purpose of this study was to investigate: (i) The use of a computer interfaced ergometer in determination of the physiological response to simulated swimming, and (ii) The relationship between this response and middle-distance swimming performance. Nine male high performance front crawl swimmers with mean 400m best time of 4:13.2 min (range 3:54.3-4:33.0 min) provided informed consent and were recruited to this study. Subjects simulated the front crawl arm action throughout a continuous incremental test, whilst the external power output (W) was displayed on a visual display unit. This allowed determination of peak oxygen consumption (VO₂peak), peak intensity of exercise (Wₚₑₚ) and exercise intensity at ventilatory threshold (VTᵳᵳ). In addition, stroke index (SI) was measured during a submaximal 400m swim and maximal body cross sectional area (BCSAₘₕₜ) determined. VO₂peak on the swim bench was 3.3 L·min⁻¹ (range 2.8-3.8 L·min⁻¹) which was at a mean Wₚₑₚ of 149.6 W (range 119-170 Watts) and mean ventilatory threshold occurred at 115.4 W (range 91-145 Watts). Only SI was significantly correlated (r = 0.75; p < 0.05) with best time for 400m (SP400). Multiple regression was performed on speed using SI, VTᵳᵳ and BCSAₘₕₜ and the correlation was 0.94 (p < 0.01). SP₄₀₀ was given by: SP₄₀₀ = 1.39 + 0.36 (SI) + 0.0026 (VTᵳᵳ) - 0.804 (BCSAₘₕₜ) explaining 89% of variation in swim performance. These results suggest that this computer interfaced simulated swimming system is valuable in assessment of high performance swimmers in the laboratory.

Introduction
The assessment of cardiopulmonary variables in the laboratory in swimmers has been problematic since derivation of these indices from exercise tests usually involves cycling or running which are known to have poor specificity with swimming (19). Also, there has not been a laboratory based device which allows the manipulation of power output for swimmers using swimming specific exercise in a similar way to that involved in treadmill and cycle ergometer testing of other athletes. As a consequence many techniques have been developed for the assessment of swimmers in the pool (4,10,16) or swimming flume (2,8).

Attempts have been made previously to assess cardiopulmonary indices in swimmers in the laboratory using a swim bench (1,13,20), however, measurement and manipulation of external power output has not been possible. Rather, the exercise intensity has been graded by manipulating stroke rate without quantification of generated power. Determination of the magnitude of increases in intensity of exercise is necessary if indices such as maximal oxygen uptake and submaximal indices of the onset of anaerobics are to be investigated.

Recently, this type of laboratory physiological data has been collected from swimmers using arm cranking and related to actual swimming performance (14). However, explanation of swimming performance must take account of drag, gross efficiency, power input from metabolism and propelling efficiency, in addition to physiological indices (23). Furthermore, active drag appears to be related to body cross-section (6) and propelling efficiency to distance per stroke (6). This would suggest that simple determination of these two variables in addition to the exercise response could provide better explanation of performance than physiological variables alone.

The computer interfaced swim bench has been validated as a swimming specific device suitable for measurement of performance during a 45 second maximal intensity exercise test. The interfacing of this
machine with a computer allows instantaneous presentation of performance as external power output. This can be presented during continuous exercise and provides the opportunity for power output to be quantified and manipulated. Also, any changes in power by this method can be met by the swimmer through freely chosen alteration in the rate or length of stroking.

The purpose of this study was firstly to investigate the suitability of this computer interfaced swim bench for assessment of swimming specific cardiopulmonary response, whilst external power output is manipulated. Secondly the purpose was to explore the relationship between the physiological variables derived from this test (in concert with indices of active drag and propelling efficiency) and middle-distance swimming performance.

Methods

Nine male swimmers of mean age 19.2 years (range 15-23 yrs) provided their informed consent and were recruited to this trial. The mean height of this group was 1.86 m (range 1.92-1.75 m) and mean body mass was 74.3 kg (range 85.6-60.8 kg). This group was selected on the basis that they were involved in high level competitive swimming. The training load of these individuals had averaged 40 km per week for the period immediately prior to the testing. Most had also recently competed at national level. Current best times were ascertained for swimming 400m. Mean speed was calculated from these times (SP), which were taken as the best performance within the 3 months prior to testing.

The experimental measures were collected in the laboratory and in the pool. In the laboratory two factors were assessed. These were firstly, an index of drag which was taken from the maximal body cross sectional area (BCSA, max) calculated as the area of a circle with equivalent circumference to that of the measured maximal body circumference (9). This was measured using a flexible steel anthropometric tape and was usually at the axillary level. Individual anthropometric characteristics of these swimmers which included BCSAMAX are given in Table 1.

Secondly, several cardiopulmonary variables were assessed on a swim bench (Euroleader U.K. Ltd., Gwent). This machine involved two rotating drum ratchet resistance devices driven by 7.5 mm diameter reinforced rope with paddles attached. These were arranged by use of pulleys so that the swimmer could generate power with each arm independently. The resistance from these devices has been investigated in detail previously (17) and could be adjusted by altering a lever setting on the swim bench console. Each resistance setting limited the maximal pull velocity that could be achieved at the hand paddles, and the action of these resistance devices has been termed biokinetic.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (Yrs)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>BCSA_{max} (m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW</td>
<td>16</td>
<td>1.75</td>
<td>60.8</td>
<td>0.92</td>
</tr>
<tr>
<td>SA</td>
<td>21</td>
<td>1.90</td>
<td>82.0</td>
<td>1.01</td>
</tr>
<tr>
<td>NM</td>
<td>23</td>
<td>1.92</td>
<td>85.6</td>
<td>1.04</td>
</tr>
<tr>
<td>BL</td>
<td>21</td>
<td>1.89</td>
<td>74.1</td>
<td>0.99</td>
</tr>
<tr>
<td>NS</td>
<td>18</td>
<td>1.82</td>
<td>64.2</td>
<td>0.94</td>
</tr>
<tr>
<td>DW</td>
<td>21</td>
<td>1.83</td>
<td>71.5</td>
<td>0.99</td>
</tr>
<tr>
<td>DH</td>
<td>19</td>
<td>1.89</td>
<td>81.2</td>
<td>0.99</td>
</tr>
<tr>
<td>CT</td>
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<td>AC</td>
<td>19</td>
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<td>1.04</td>
</tr>
<tr>
<td>Mean</td>
<td>19.2</td>
<td>1.86</td>
<td>74.3</td>
<td>0.99</td>
</tr>
<tr>
<td>SD</td>
<td>2.6</td>
<td>0.05</td>
<td>3.0</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Setting number 4 was chosen (on a range of 0-6) since this allowed a maximal pull velocity of 2.0 m s^{-1} which has been shown to be optimal (17). Subjects were allowed to generate power by freely chosen combinations of stroke rate and length. At maximal intensity exercise stroke rates were 43 min^{-1} (range 39-47) which has been shown to be optimal for testing performed on a similar swim bench (20).

The swimmers adopted a prone position on the bench and were anchored by use of a belt around the belly of the hamstring muscles. Assessment of a series of physiological variables was made throughout a continuous incremental exercise test to exhaustion which involved simulated front crawl swimming (alternating arms).

The interfacing was achieved via an RS232 output port on the bench console and serial input port on the microcomputer. The 8-bit data string was computed by use of specialised software (University of Sunderland) which assimilated the force, distance and time data during each arm pull. This data was sampled at a rate of 100Hz by the swim bench microprocessor which allowed mean power output for each arm pull to be computed. External power output (W) was computed from averaged values for both arms for a 10 second period.

During this simulated swimming test continuous measurements were made of expired gas O_2 and CO_2 concentration and flow rate which allowed calculation of oxygen consumption (VO_2), carbon dioxide output (VCO_2), minute ventilation (V_e). VO_2 and VCO_2 were measured using paramagnetic and infra-red analysers respectively (Servomex, Crowborough, U.K. and Mijnhart, Odijk, Netherlands) and V_e measured by use of a gas turbine (Parkinson Cowan) on expiration. This was done by use of an electronic optical reader attached
to a rotating turbine driven by a sliding valve and rod system. The expired gas was mixed in a 5 Litre chamber before being sampled. Values from the gas analysis were averaged and recorded every 30 seconds. Heart rate (HR) was measured using radio telemetry (Polar, Finland) and band electrodes attached over the myocardial apex. The values were recorded each 3 second interval.

Swimmers were instructed to maintain their level of external power output (as given by a moving cursor) within a target display band on the visual display unit of the microprocessor as represented in figure 1. The target power output commenced at 25 watts and was then increased by 7.5 watts each minute. Subjects were asked to continue “swimming” until exhaustion and were encouraged to maintain maximal stroke length. The peak oxygen consumption ($VO_{2\text{pk}}$) was defined as the highest oxygen consumption that subjects could attain whilst maintaining the average (10 seconds) external power output (W) within 3 watts of the computer generated target power.

This testing allowed determination of $VO_{2\text{pk}}$, $W_{\text{pk}}$ and $R_{\text{pk}}$. All swimmers were accustomed to this swim bench model however none had performed any training programmes on this equipment for at least four weeks prior to the experimentation. All swimmers were allowed familiarisation with the physiological equipment by rehearsal of the test procedure. Also, the subjects were asked to refrain from arduous exercise training for at least 24 hours prior to the testing. Subjects were 1-2 hours post absorptive.

In the swimming pool an index of stroke effectiveness in 400m swimming was measured by asking each swimmer to complete 400m in the shortest time adopting a stroke technique which produced maximal distance per

<table>
<thead>
<tr>
<th>SWIM TIME : 1:36</th>
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</thead>
<tbody>
<tr>
<td>TARGET POWER : 50</td>
</tr>
<tr>
<td>ACTUAL POWER : 49</td>
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</table>

Figure 1. Representation of the feedback information (as shown on the microcomputer visual display unit) used to manipulate the exercise intensity during simulated swimming. The broken line represents ±3 Watts of target power within which swimmers were asked to maintain their generated power output.
stroke. From this swim a stroke index (SI) was calculated as the product of the mean speed (SI_{sp}) and the mean distance per stroke (SI_{ps}). This is similar to an index determined by Costill et al. (4).

Piecewise linear regression (24) was performed on the plot of \( V_e/VO_2 \) to identify the exercise intensity at the ventilatory threshold (\( VT_w \)) as detailed by Orr et al. (15). The sum of least squares from line fitting was analysed for best fit of a single line versus an intersecting broken line, before the breakpoint ventilatory threshold was accepted. From this plot, the VO_2 at the \( VT_w \) could also be recorded and related to VO_2pk. This measure of the fractional utilisation of VO_2pk (VO_2Fr) when expressed as percentage is similar to that used in studies of running performance (12). Pearson's product moment multiple correlations were calculated with speed for best time at 400m (SP_{400}) as dependent variable and SI, BCSA_{max} and selected swim bench cardiopulmonary measures as independent variables.

Results

The swim bench assessments provided peak physiological measures which included VO_2pk, W_{pk}, R_{pk} and HR_{pk}. Also, it was possible to determine a sub-maximal variable \( VT_w \). Mean VO_2pk values were 3.3 L.min^{-1} (range 2.8-3.8 L.min^{-1}). The mean value for peak exercise intensity (W_{pk}) was 149.6 watts (range 119-170 watts) and R_{pk} was 1.13 (range 1.08-1.17). The mean \( VT_w \) was 115.4 watts (Range 91-145 watts). The mean VO_2Fr was 84.33% (range 72.1-94.6%). The individual values and means (SD) are given in Table 2. The measurement of heart rate during exercise was only possible in five of the nine subjects due to the discomfort of the band electrodes around the thorax whilst positioned on the bench. The mean HR_{pk} was 182 b.min^{-1} (range 171-190 b.min^{-1}). The piecewise analysis of \( V_e/VO_2 \) successfully detected breakpoints in all subjects and these analyses are given in Figure 2. The mean SI_{DS} from the stroke index assessment in the pool was 1.31m (range 1.17-1.53 m). The pool test indices and swimming performance mean speeds (SP_{400}) are given in Table 3.

Table 3. 400m Swimming Variables

<table>
<thead>
<tr>
<th>Subject</th>
<th>SP_{400} (m/s)</th>
<th>SI (m/s)</th>
<th>SI_{sp} (m/s)</th>
<th>SI_{ps} (m/s)</th>
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<tbody>
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<tr>
<td>AC</td>
<td>1.67</td>
<td>2.32</td>
<td>1.53</td>
<td>1.53</td>
</tr>
<tr>
<td>Mean</td>
<td>1.58</td>
<td>1.87</td>
<td>1.44</td>
<td>1.31</td>
</tr>
<tr>
<td>SD</td>
<td>0.09</td>
<td>0.21</td>
<td>0.78</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 2. Incremental Test Variables

<table>
<thead>
<tr>
<th>Subject</th>
<th>VO_{2pk} (L.min^{-1})</th>
<th>HR_{pk} (b.min^{-1})</th>
<th>W_{pk} (W)</th>
<th>Prk</th>
<th>VT_{w} (W)</th>
<th>VO_{2Fr} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW</td>
<td>2.9</td>
<td>---</td>
<td>119</td>
<td>1.14</td>
<td>91</td>
<td>91.9</td>
</tr>
<tr>
<td>SA</td>
<td>3.6</td>
<td>---</td>
<td>170</td>
<td>1.10</td>
<td>145</td>
<td>94.6</td>
</tr>
<tr>
<td>NM</td>
<td>3.8</td>
<td>---</td>
<td>161</td>
<td>1.08</td>
<td>111</td>
<td>76.9</td>
</tr>
<tr>
<td>BL</td>
<td>3.6</td>
<td>---</td>
<td>159</td>
<td>1.13</td>
<td>145</td>
<td>88.9</td>
</tr>
<tr>
<td>NS</td>
<td>2.8</td>
<td>187</td>
<td>131</td>
<td>1.16</td>
<td>114</td>
<td>94.6</td>
</tr>
<tr>
<td>DW</td>
<td>3.1</td>
<td>171</td>
<td>159</td>
<td>1.18</td>
<td>103</td>
<td>72.1</td>
</tr>
<tr>
<td>DH</td>
<td>3.8</td>
<td>179</td>
<td>160</td>
<td>1.13</td>
<td>105</td>
<td>75.5</td>
</tr>
<tr>
<td>CT</td>
<td>3.0</td>
<td>190</td>
<td>133</td>
<td>1.12</td>
<td>119</td>
<td>89.8</td>
</tr>
<tr>
<td>AC</td>
<td>3.4</td>
<td>186</td>
<td>153</td>
<td>1.17</td>
<td>106</td>
<td>73.8</td>
</tr>
<tr>
<td>Mean</td>
<td>3.3</td>
<td>182</td>
<td>149.6</td>
<td>1.15</td>
<td>115.4</td>
<td>84.3</td>
</tr>
<tr>
<td>SD</td>
<td>0.4</td>
<td>8.0</td>
<td>17.1</td>
<td>0.03</td>
<td>18.4</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Correlation of SP_{400} with the experimental variables from swim bench, pool test and anthropometry showed an absence of significant correlation in all but stroke index (SI) from the pool test. The correlation coefficients are given in Table 4. None of the swim bench physiological indices was correlated with swimming performance in this group of subjects. However, when the swim bench indices were added selectively to the correlation of stroke index with SP_{400} the multiple regression analysis showed that the correlation was found to improve with some indices from the swim bench and deteriorate with others.

Table 4. Correlation of 400m Swimming Performance With Swim Bench Indices, Stroke Index and BCSA_{max} *

<table>
<thead>
<tr>
<th>SI_{sp}</th>
<th>SI_{ps}</th>
<th>SI_{DS}</th>
<th>VO_{2pk}</th>
<th>W_{pk}</th>
<th>Prk</th>
<th>VT_{w}</th>
<th>VO_{2Fr}</th>
<th>BCSA_{max}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.54</td>
<td>0.52</td>
<td>0.75*</td>
<td>-0.02</td>
<td>0.30</td>
<td>0.05</td>
<td>0.31</td>
<td>0.46</td>
<td>0.23</td>
</tr>
</tbody>
</table>

*denotes significance p<0.01

When peak exercise intensity indices were included the multiple correlation did not improve from 0.75 (for SI alone) for VO_{2pk} inclusion and only improved to 0.79 on addition of W_{pk}. However, when VT_{w} was included the multiple correlation increased to 0.89 which was significant (p<0.01). Furthermore, addition of a third independent variable of BCSA_{max} increased the correla-
Figure 2. The plot of the ratio of minute ventilation to oxygen consumption ($V_E/VO_2$) against exercise intensity ($W$) for all subjects on the swim bench. The lines indicate piecewise regression sum of least squares best fit enabling exercise intensity at the breakpoint ($VT$) to be determined.
tion to 0.95 (p<0.01) with these three factors accounting for 89% of the variation in \( SP_{400} \). The regression equation for this multiple correlation analysis was:

\[
SP_{400} = 1.39 + 0.36 \text{(SI)} + 0.0026 \text{(VT,)} - 0.804 \text{(BCSA,)}
\]

Further exploration was made of the influence of \( SI_{sp} \) on the correlation of SI with \( SP_{400} \) since the determination of SI included a measure of swimming speed for the 400m (\( SI_{sp} \)). However, when the swimming speed from the stroke index pool test (\( SI_{sp} \)) was correlated with best performance speed (\( SP_{400} \)) the correlation between these two variables was not significant (0.54, p>0.05).

The \( VO_{2F} \) was not correlated with \( SP_{400} \), but multiple correlation again showed that \( SP_{400} \) was correlated with a combination of SI and \( VO_{2F} \) (\( r=0.91, p<0.01 \)).

400m swimming performance was given by:

\[
SP_{400} = 0.43 + 0.39 \text{(SI)} + 0.005 \text{(VO_{2F})}
\]

**Discussion**

The results of the swim bench testing appear to show that this computer interfaced swimming ergometer offers the opportunity for standardisation of assessment of swimmers by use of a testing protocol involving quantifiable changes in power output in the laboratory. The ability to manipulate power output during simulated swimming also offers the opportunity for assessment of other indices of performance such as the onset of blood lactate accumulation.

The \( VO_{2p} \) values obtained from this study are comparable to those from other studies of swimmers using arm ergometry (14) but tend to be closer to those values reported for free swimming (11). This could be explained firstly by the specificity of swim bench exercise which is closer to that of actual swimming than any other laboratory based ergometer since the arm action of actual swimming is simulated.

Secondly, the higher \( VO_{2p} \) values here may be due to better arrangement of the presentation of increases in exercise intensity, since in this test the power output was quantified and increased at a known rate. Such aspects of ergometer exercise testing protocols are known to affect \( VO_{2max} \) (18).

It is acknowledged that this type of ergometry predominantly exercises upper body musculature and this might detract from a relation to actual swimming where of course there is a significant contribution to propulsion from the legs. This could lead to greater discrepancy between pool performance and swim-bench measures in the sprint swimmers since it is well established that the contribution of the leg propulsion to overall performance is greater in these individuals (5).

It also appears from our results that for a homogeneous group of high performance swimmers such as those used here, maximal physiological responses to simulated swimming such as \( VO_{2p} \) and \( W_{p} \) might not explain differences in performance in middle distance swimming. This is contrary to the results of other studies (4,14) who reported a positive correlation between swimming times and \( VO_{2max} \) for a group whose abilities were heterogeneous. No such relationship was identified in this study in which swimmers were more homogeneous.

As with studies on runners (3) this supports the suggestion that \( VO_{2max} \) is an insensitive indicator of endurance in highly trained performers. Of greater value are physiological indices which indicate increased dependence on anaerobiosis such the onset of blood lactate accumulation, or gas exchange indices such as \( VT_{p} \) and \( VO_{2F} \). This would again accord with studies on athletes using such indices as the onset of blood lactate accumulation (7). Values for \( VO_{2F} \) compare well in this study with those for runners (12).

The correlation of stroke efficiency indices with swim performance has been shown before (4,22). The results here support this finding since stroke index from the submaximal swim was the sole variable to correlate with swimming best times. This reiterates the importance of the effectiveness of the swimming stroke in determining performance.

Swimming performance is known to be determined by the concerted effects of several principal variables which have been discussed before (23). The multiple correlation analysis of swimming speed for 400m in this study demonstrated a strong relation between these variables and swimming performance for 400m. Furthermore these variables can be easily determined using the computer interfaced swim bench with other simple tests. This suggests a value for this equipment in assessment of swimming performance especially when determined in concert with other simple laboratory and pool measures.

**Practical Applications**

The findings of this study provide the basis upon which assessment of swimming performance can be made in the laboratory. This is of particular relevance to those coaches and sports scientists involved in performance monitoring of swimmers. The two main predictors of success in 400m swimming can be monitored and evaluated with these assessments. However, the laboratory testing must be supplemented with the simple pool measure of stroke index in order for there to be any relationship with swimming performance. This relationship is likely to exist only in those events where the leg kick is de-emphasised.

Of perhaps greatest practical importance are the opportunities made available through the technological developments of the swim bench (as made by the author). The interface system provides a method by
which the work rate or power output of the swimmer on the swim bench can be controlled very precisely. This means that the use of the swim bench for training purposes will be much easier and can be structured. Not only can the pull velocity be manipulated as before, but now the intensity of effort can be carefully adjusted. This would allow any combination of exercise duration and intensity to be chosen very accurately. With information from a simple test, training programmes on the swim bench can be tailored to suit individuals. The programme could involve combinations of intervals of any duration from 30 sec to 5 minutes with intensity being carefully chosen according to the required effect. This training could even be targeted in this way at the "anaerobic threshold" type levels in quite a precise manner.

Furthermore, the computer interfaced swim bench system offers the opportunity to analyse stroke characteristics. This can be done on each arm throughout any work period. The force profile can be displayed on the screen or printed so that swimmers can see at-a-glance such technique indicators as stroke continuity, length, rate and the balance of work rate between left and right arm. For example, all of these stroke indicators can be displayed during exercise training intervals, so that the swimmer can view the changes in stroke technique characteristics under the influence of fatigue. There has yet to be conclusive research which allows the force profile to be matched to the stroke phases as performed in the water. Nevertheless, Thornton and Flavell developed some principles of stroke analysis from swim bench for profiles some years ago (See Biokinetic Strength Training, pp 60. Isokinetics Inc. Albany, CA, 1981).

This system offers further opportunities for use of the swim bench in rehabilitation after injury in the swimmer. The re-development of power in each arm and the balance of the two sides can be assessed during the swimming action. This was not possible until now. The ability to perform interval training sessions at carefully chosen intensities is also of value to triathletes. It is possible with this system to simulate the transition from swim to bike using predetermined interval efforts. This specific training has been developed for bike to run, but not for swim to bike.

Summary

1. 400m performance can be predicted very precisely with swim bench test measures if they are added to stroke index scores.

2. Improvement in 400m performance can thereby be identified as either improvements in exercise conditioning (fitness) or improvements in stroke technique.

3. The computer interfaced swim bench can be used much more effectively in dry land interval training through much more precise manipulation of exercise duration and intensity.

4. The computer interfaced swim bench can be used to make some general analyses of stroke technique during dry-land training.

5. Rehabilitation programmes can be more appropriately structured and recovery from injury can be monitored.

6. Triathletes could use this system for effective dry-land swim-to-bike transition training.

References


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In Print: Swimming '89

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Abstract
The idea of a scientific journal specifically dedicated to enhance communication between scholars interested in competitive swimming, and the professional practitioners in the sport, i.e., coaches, originated from the late Keith Sutton. His vision was that JSR would serve the American and indeed the international swimming community by acting as an educational forum without a compromise in scientific rigor. In this way, JSR would serve researchers seeking an attentive, appreciative audience as well as serve those who wish to apply recent results obtained from the frontiers of science. One of Keith's original concepts is actualized by that which follows, a bibliography of publications relevant to the swim community. It is hoped that this bibliography continues to represent a useful guide to information relevant to coaches, swimmers and researchers.

BIOMECHANICS

GENERAL


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Noden, M. (1989, Apr.). He had’em goggle-eyed (Dave Wharton named Swimmer of the Year at NCAA championships). *Sports Illustrated*, p. 82(1).


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“A Re-evaluation of forces . . .”
1. Propulsive forces in swimming include lift and ______ forces.
2. In 1933 Karpovich described resistances encountered in swimming as being skin friction, ______ resistance, and wave-making resistance.
3. ______ is defined as the component of force acting perpendicular to the drag force.
4. In freestyle, the contribution of the forearm to propulsive drag forces increases with speed of swimming and surpasses the hand’s contribution at ______ m/sec.
5. ______ drag is caused by the shape (geometry) of the swimmer.
6. Form drag can be decreased by ______.

“Differences in peak blood lactate . . .”
7. Blood lactate concentrations after an all-out swim are ______ in short course pools than in long course pools.
8. This effect was hypothesized to be due to the ______ in short course which provides relative inactivity of ______ muscles.
9. Swimmers trained in short course pools may be at a disadvantage when competing in long course pools because they may be more susceptible to lactate-caused ______.

“Carbohydrate ingestion . . .”
10. The purpose of carbohydrate feedings during long training sessions is to help prevent a decline in blood ______ during the half of the training session.
11. Carbohydrate feedings during a swim practice improved performance on a set of 10x100/1:20 late in the practice only in those swimmers who experienced ______ during the control condition.
12. The carbohydrate feedings had what effect on the blood lactate responses to the training session? ______

“The relationship between physiological variables . . .”
13. Stroke effectiveness was defined as the product of mean speed over 400 m and ______.
14. The best combination of measured variables in predicting or correlating with 400 m performance was stroke index, ______, and ______.
15. ______ is an insensitive indicator of endurance in highly trained athletes.
THE JOURNAL OF SWIMMING RESEARCH

—AUTHOR GUIDELINES—

(Revised May, 1980)

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