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THE JOURNAL OF SWIMMING RESEARCH

CONTENTS

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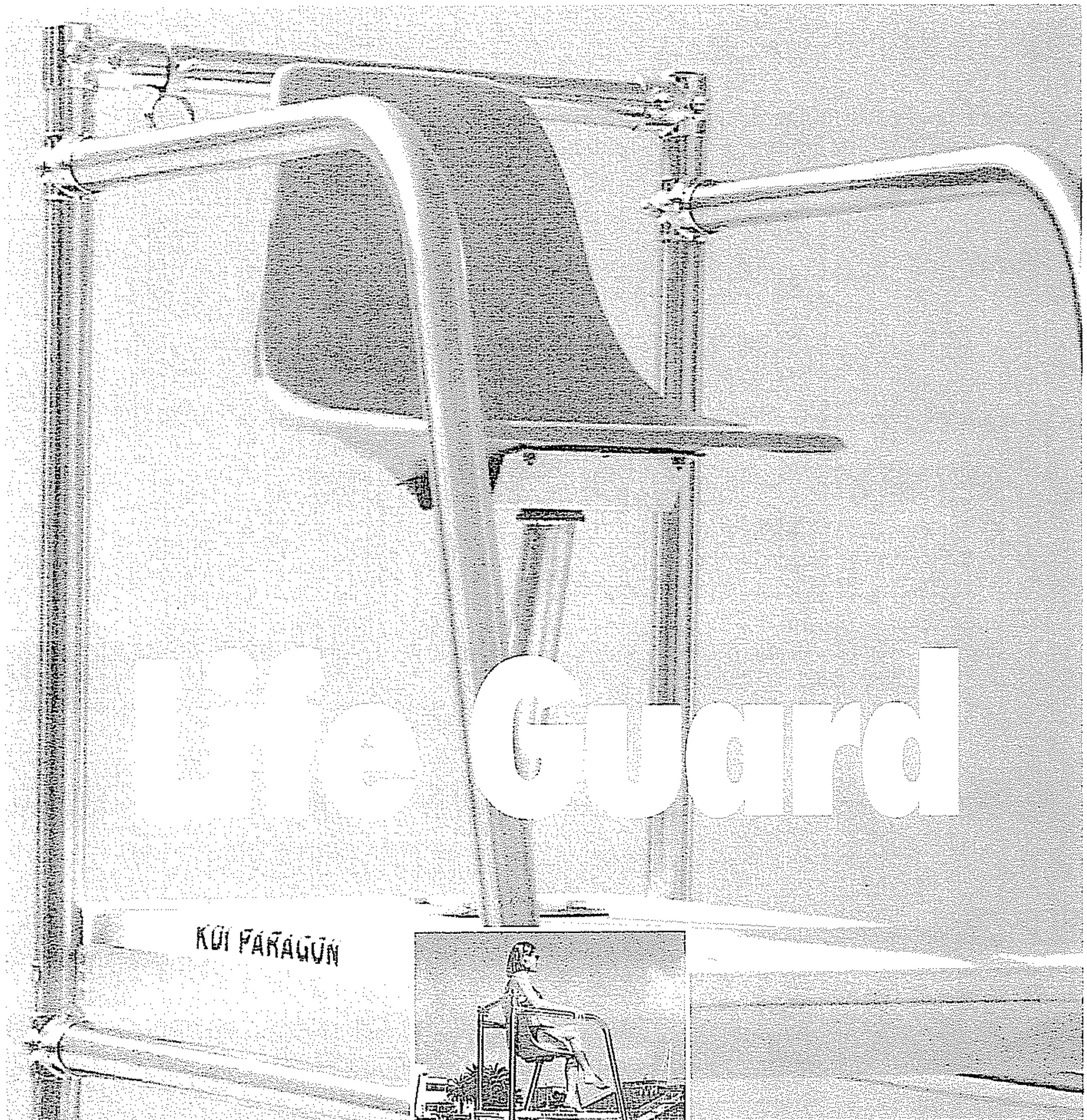

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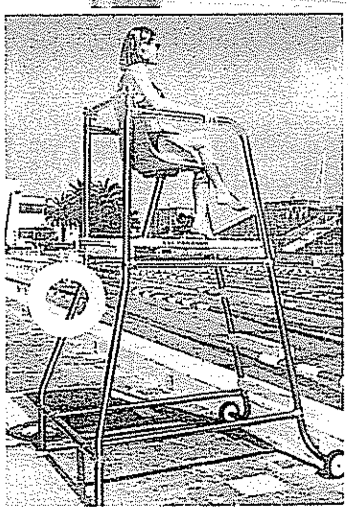

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THE JOURNAL OF
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Joel M. Stager, Ph.D.
Publisher & Editor-in-Chief, *JSR*

William H. Brechue, PhD
Indiana University

Jane Cappaert, M.S.
United States Swimming

Loren Cordain, PhD
Colorado State University

Jim Hay, Ph.D
University of Iowa

Tim Henrich, Ph.D.
Incarnate Word College

Kelli Koltyn, PhD
University of Florida-Gainesville

Rick Latin, PhD
University of Nebraska-Omaha

Scott McLean, PhD
Iowa State University

Brett Mills, PhD
United States Sports Academy

Jan Prins, Ph.D.
University of Hawaii

Jack Raglin, PhD
Indiana University

Rick Sharp, PhD
United States Swimming

Bill Thomas, M.S.
Incarnate Word College

Ellen Thorson, PhD
University of Iowa

Scott Trappe, PhD
Ball State University

Maloni Trine
University of Wisconsin

Jaci VanHeest, PhD
United States Swimming

Peter Vint, PhD
Arizona State Unversity

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A changing of the guard

The Journal of Swimming Research was initiated in 1984 during Keith Sutton's tenure as Executive Director of ASCA. Since that time it has received continued support and enthusiasm from John Leonard and ASCA's board of directors. Mary Sutton worked tirelessly as publisher and editor during the first seven years of *JSR*'s existence. Her guidance and devotion to the *Journal* helped to establish it as a legitimate communication venue and important information source unique among competitive athletics. In the fall of 1989, Rick Sharp took over Mary's responsibility with the *JSR* and in good stead continued in this role until the present issue. Rick now heads the International Center for Aquatic Research for USS in Colorado Springs. In this capacity he continues to pursue knowledge relevant to improving the performance, health and general welfare of the competitive swimmer. With the current issue, Joel Stager has assumed the duties, responsibilities, and as Rick put it, the "honor" of the position of Editor-in-Chief for *JSR*. The *JSR* will go through changes, albeit minor, as a result of this change in leadership. The editorial office will move a few hundred miles eastward, to Bloomington, Indiana, where Stager is currently the Director of the Human Performance Labs at Indiana University. This move perhaps is fitting as it was Doc Councilman who put Bloomington and IU on the international aquatic map with his introduction of the scientific approach to coaching.

Joel's background in swimming is lengthy. Learning to swim became a priority for him following a near drowning at age 12 on the Tionesta River in Pennsylvania. When the local school district opened a new swim facility, Coach Dave Tompkins was desperate enough for prospective swimmers that he accepted all comers. It quickly became apparent that although Stager could definitely swim, he couldn't swim indefinitely, and thus, rest, recovery and taper became Stager trademarks. Following high school, Stager attended the University of Miami (Fla) and swam during the David Wilkie era graduating in 1975 with a BS in Biology, a minor in Chemistry and, as he puts it, "a very limited wardrobe and a great tan."

A chance meeting with Doc Councilman convinced Stager to attend Indiana University in Bloomington for graduate study. Thanks to Doc's encouragement, he completed his PhD in Medical Physiology in 1980 with a renewed interest in the science of swimming. In the 80's, Stager began a series of federally funded research projects relevant to swimming at Colorado State University in Ft. Collins. He then accepted a position at IU and holds the academic rank of associate professor.

Joel has served as a member of the USS Sports Science Committee and has been funded through the USOC Elite-Athlete Program. He has served as an Associate Editor for ASCA and the JSR since its inception and participates in the peer-review process for many scientific journals. Joel continues to maintain an active research interest in swimming and a strong graduate program at IU. Joel's two children are both competitive swimmers in Bloomington and he has acted as meet director, board member and graphic designer for the Bloomington Swim Club. Joel remarks that he continues to perfect his tapering technique and has become an accomplished bubble blower while preparing for US Masters Swimming events.

Despite a changing of the guard, the *JSR* will remain dedicated to the peer-review process and thus, greatly dependent upon the volunteer spirit of the scientific community. The *Journal* will continue to strive towards being responsive and relevant to the competitive swim community. Input and assistance from any source: coaches, swimmers, scientists, trainers, educators, etc., in terms of content or perspective is welcomed. It is the mission of the *JSR* to provide a source of knowledge that is independent of commercial interests, unbiased in perspective and founded upon established fact. Whether or not it is truth that is published here remains to be determined, dependent upon the test of time and independent verification by others.

Editor's Preview

Scholarship, research, and science in swimming

My copy of Webster's College Dictionary doesn't differentiate much between "scholarship," "research" and "science." Scholarship is defined as the quality of knowledge and learning; systematized and exhibiting accuracy, critical ability, and thoroughness. In contrast, the meaning of research is careful, systematic, patient study and investigation of some field of knowledge undertaken to discover or establish facts. Finally, science is defined by Webster to be systematized knowledge derived from observation, study and experimentation in order to determine the nature or principles of what is being studied. The differences are as clear as the rules governing the backstroke flip turn, right? Or is it just me? Certainly, there are similarities among the three and subtle differences are apparent.

The first article, "Computational fluid dynamics: an analytical tool for the 21st-century swimming scientist," appears to be a good example of **scholarship**. In order to discover ways for swimmers to swim faster, we have only two choices. We can study fast swimmers and hopefully determine what it is that makes them so. The alternative is to understand the physical principles which determine and/or limit speed in the water and attempt to apply these principles to our swimmers. Bixler and Schloder suggest that it is time we use the latter approach. Defending the article, Bixler writes "*I do not expect the 'typical' coach or even most 'swimming scientists' to understand the details of CFD. To do so would require an in-depth education in mathematics, fluid mechanics, and numerical analysis, as well as significant experience in evaluating complex fluid flow situations. However . . . it is my hope that (the article) will open the eyes of coaches and swimming scientists to the powerful tool that is available to them.*" In my mind, this article is a true example of scholarship, certainly appropriate for the *JSR*.

The purpose of the second article, "Use of swim-training profiles and performance data to enhance training effectiveness," is to determine whether or not the effects of various training practices on a swimmer may be identified in an objective manner using straightforward measurements readily available to the coach. This article appears to fulfill Webster's definition of **science**. Mujika and co-authors extend their previous findings by illustrating how training and performance information can be used to evaluate individual responses. From this, subsequent training programs can be designed resulting in more optimal responses and enhanced performance for the individual. Observation, study and experimentation: science at its best.

The third article, "Recovery from maximal swimming at the predicted onset of blood-lactate accumulation," by Richardson, et al, **researches** the troublesome topic of recovery. For those who are interested in lactic acid and its use as a coaching/training tool, this article provides insight into the complex issues which surround it. As in the prior article, the importance of identification of the individual's response is emphasized. Provided is information for coaches that will allow application of science-derived knowledge.

The effect of sweating and dehydration upon endurance running performance is well known. That swimmers may experience similar problems is less obvious. The fourth article, "Fluid loss in swimmers," by Reaburn, et al, is a demonstration of what might be considered a profound effect of a swim training bout. Despite being in, under, and on top of the water, swimmers participating in a typical competitive workout lost weight equivalent to nearly a liter of water. Consideration of this must be made in order that fluid loss during practice is not limiting to performance per se.

One approach to identifying the important factors which account for quick freestyle flip turns is the application of powerful statistics upon empirical data. In the article, "Force plate and video analysis of the tumble turn by age-group swimmers," Blanksby and co-authors identify a number of flip turn components which may be critical in terms of accounting for differences among age group swimmers. Their research could have dramatic implications by allowing coaches to focus upon aspects of the turn which are most important and therefore most effective as far as reducing swim times.

Finally, to assist in the scholarship of the competitive-swimming community, the final selection prepared by Tanner is an installment of the "In Print" series. It is our hope that this compilation will be a time-saver for ASCA members and will stimulate further scholarship and research among the swimming community.

In closing, this issue of the *JSR* is a combination and blend of scholarship, research and science. It is the next effort in the process of adding to the body of knowledge as it pertains to competitive swimming. To paraphrase from Robert Persig, the truths held within are not dogma, good for eternity, but temporal quantitative entities. Through science, research and scholarship, the time required to advance the sport may be shortened. Science and scholarship are more efficient processes than trial and error.

I would like to thank the authors, associate editors and reviewers for their contributions to this effort. The challenges ahead are to read, think, apply and, of course, test the ideas and concepts here presented.

J. M. STAGER

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Computational Fluid Dynamics: An Analytical Tool for the 21st Century Swimming Scientist

BARRY BIXLER AND MONIKA SCHLODER

Allied Signal Aerospace
Phoenix, Arizona

Abstract

Computational Fluid Dynamics (CFD), a methodology developed by engineers to numerically solve complex problems of fluid flow using computers, is introduced as a tool to evaluate the fluid flow around a swimmer's body or extremities. CFD is defined, and the steps necessary to set up a CFD analysis of fluid flow are presented. CFD analyses are performed for the steady and accelerated flows of water around a disk having the same area as a typical swimmer's hand. Combinations of velocity and acceleration were chosen to be within or near the range of typical hand velocities and accelerations generated by freestyle swimmers during the freestyle insweep or upsweep. Drag forces determined from these analyses show that hand acceleration may increase propulsive drag above quasi-steady values by as much as 40%. This drag increase is approximate because it was calculated using a CFD model of a disk, rather than a more complex CFD model of a hand. However, the principles of fluid dynamics which increase the drag on a disk in accelerated flow also apply (with adjustments for changes in Reynolds number), to a hand or any other shape. Therefore, an increase in the propulsive drag of a hand due to acceleration is also to be expected.

The poolside application of these results is that coaches should encourage their swimmers to accelerate their hands from start to finish of their freestyle sweeps, rather than move them at a constant velocity (especially during the insweep and upsweep). This is what Counsilman intuitively advised many years ago, and now we have the scientific proof that this is indeed the correct approach.

These initial results show that more complex CFD models of actual arms and hands are worth building and analyzing, where Reynolds number and the angle of attack are additional variables to be considered. Such models will provide a more accurate assessment of the effect of acceleration on the propulsive drag and the propulsive lift of a swimmer's hand. The authors have work in progress doing just that, and as additional and more complex analyses are performed, a database of drag and lift coefficients for use in unsteady flow conditions can be developed to assist in the evaluation and improvement of stroke technique.

Also during this study, the added mass concept is summarized and is shown to provide a mathematical explanation for why some coaches intuitively encourage their swimmers to "grab" as much water with their hands as possible. In addition, a study of engineering literature has revealed that the propulsive drag and lift forces developed by a swimmer's hand (or any body part) at a given time are dependent not only upon the size, orientation, shape, and velocity of a swimmer's hand at that time, but also upon the acceleration at that time and upon the acceleration history of the hand prior to that time. And finally, it is shown that The Principle of Relative Motion is only valid for steady flow. For unsteady flow, the force on a stationary body in an accelerating fluid is greater than the force on a body accelerating through a stationary fluid by a factor called the horizontal buoyancy force. In a swimming flume, although the water velocity may be held constant, a swimmer's arms and legs are accelerating and decelerating. Thus, the horizontal buoyancy force is one factor that may account for a swimmer's flume performance being different from his or her pool performance.

INDEX TERMS: CFD, Fluid Dynamics, Propulsive Drag Force, Unsteady Flow, Hand Acceleration, Stroke Acceleration, Fluid Added Mass, Freestyle Insweep, Freestyle Upsweep

Introduction

In the second century B.C., after discovering the solution of the problem to move a given weight by a given force, Archimedes is said to have boasted to King Hiero of Syracuse, "give me a place to stand on and I can move the earth." Archimedes was called upon to demonstrate what he meant, and he made a machine by which he pulled a large fully loaded ship out of dock using only one arm. By first understanding the principles of the problem, and then using or developing a tool which properly applied those principles, Archimedes acquired, according to Plutarch, "the renown of more than human sagacity." Archimedes made a name for himself by creating an assortment of novel weapons for King Hiero, and when the Romans attacked Syracuse these weapons were so successful, that it was only through treachery that they finally took the city.

So what does this have to do with swimming? Archimedes' approach to problem solving is worthy of our emulation. In fact, the spirit of his approach has already been promoted within the swimming community. Nigg (14) and Clarys (5) have emphasized the importance of understanding the basic principles of swimming mechanics through systematic and fundamental investigations. Leonard (12) has encouraged coaches and swimming scientists to develop a

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"toolbox" of information gathered from as many sources as possible, and to expand it at every opportunity. Hay (8) has stressed the need "for researchers to be much more alert than in the past to the opportunities that developing technologies provide and to take advantage of those opportunities without delay." As demonstrated so well by Archimedes, improved tools or technology, if properly used, can facilitate reaching a speedy and accurate solution to a problem.

One available tool not yet utilized by the swimming community is called Computational Fluid Dynamics (CFD). CFD is a methodology developed by engineers to numerically solve complex problems of fluid flow using modern high speed digital computers. Engineers use CFD to evaluate external fluid flow around airplanes, cars, and ships, and internal flow through gas turbine engines and piping systems. Based upon these analyses, they are able to design more streamlined airplanes, cars and ships, and to design more efficient engines and piping systems. In the same manner, CFD may be used to evaluate the fluid flow around a swimmer's body or extremities, calculating the fluid pressure, velocity, and lift and drag forces. It then may be used as a tool to "design" a better stroke, kick, or body position for swimmers. CFD is a powerful tool, and holds great potential for increasing our knowledge about swimming fluid dynamics.

It has been "echoed" throughout the swimming community that modern coaching is now an art and a science, and coaches have welcomed much valuable information from the academic community and other experts in the scientific fields of physiology, nutrition, etc. However, other fields such as physics or engineering, which rely heavily on advanced mathematics, are sometimes perceived as too hypothetical or too difficult to understand. To minimize this problem, the authors have included a review of fluid dynamic principles relevant to the present paper, and have separated the paper into two parts. The first part is the main body of the paper, and it contains only the minimum technical information necessary to read the paper. The second part is an appendix composed of additional technical information that is pertinent to the paper, but is not necessary to understand the results.

Purpose of The Present Paper

The purpose of the present paper is twofold: First, introduce CFD to the swimming community, and second, apply it to a simple foundational problem upon which future research may be built, and which allows the reader to calculate a "first approximation" of the effects of accelerated motion on the propulsive drag force of a hand. This application is just the "tip of the CFD iceberg", and there are dozens of ways in which CFD may be applied to swimming. There will come a time when the results of CFD analyses will be routinely used by coaches to either "fine-tune" a swimmer's strokes or to radically change them. Several specific ways in which CFD may be applied to swimming will be presented later in this paper after CFD is defined.

Methodology

CFD Defined

CFD is a mathematical model of fluid flow that can be solved on a computer. Think of CFD as a desktop wind-tunnel or swimming pool. A CFD model consists of a two or three dimensional grid or mesh of "cells" which follow the geometry of the fluid flow. Fluid properties, flow characteristics along the outside grid boundaries, and a mathematical relationship to account for turbulence are added to this grid. Then the model is "analyzed" by a computer which calculates pressure, velocity, drag force, lift force, and other such quantities throughout the grid.

Although CFD users must be familiar with fluid dynamics principles and numerical techniques, they don't have to write their own CFD computer programs. CFD methodology has been packaged into commercially available programs by various software companies for use on PCs, workstations, and mainframe computers. A summary of the steps involved in setting up a CFD analysis using one of these commercially available codes is given in the Appendix. The basic solution process used by many of these programs is shown in the flowchart of Figure 1. Although some elaboration of this solution process is stated in the Appendix, the detailed numerical techniques contained within such codes are not the focus of the present paper. Interested readers are referred to Anderson, Tannehill, and Pletcher (1) and Peyret and Taylor (16).

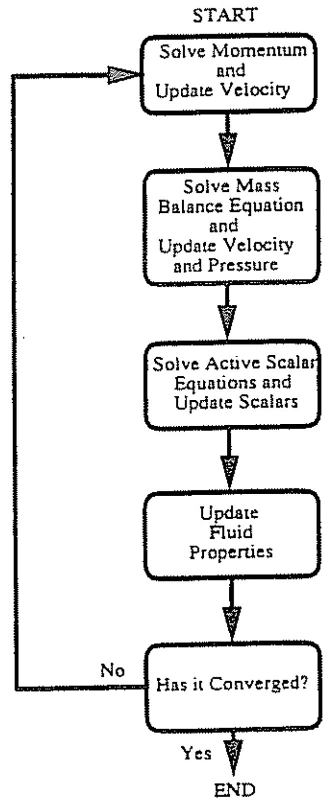

Figure 1. Flowchart of the Solution Process

A Non-Swimming Example of a CFD Analysis

The present paper is the first exposure of most readers in the swimming community to CFD. To help demonstrate the power of the technique, a CFD model typical of those developed by aerodynamic engineers to analyze the flow of hot gas around jet engine turbine blades is shown in Figure 2 [Pfeifer (17)]. Although the CFD grid along the boundaries of the model may be clearly seen, the grid between the model boundaries has been removed for clarity. From this model, the aerodynamicist can determine the fluid pressure and velocity field distribution along and between the blade surfaces, as well as the energy loss as the gas moves through the blades. The fluid particle path plots shown in Figures 3 and 4 reveal the complex flow at the hub (bottom) and tip of the blades, including the formation of hub "horseshoe" vortices, as well as vortices being shed from the blade tips.

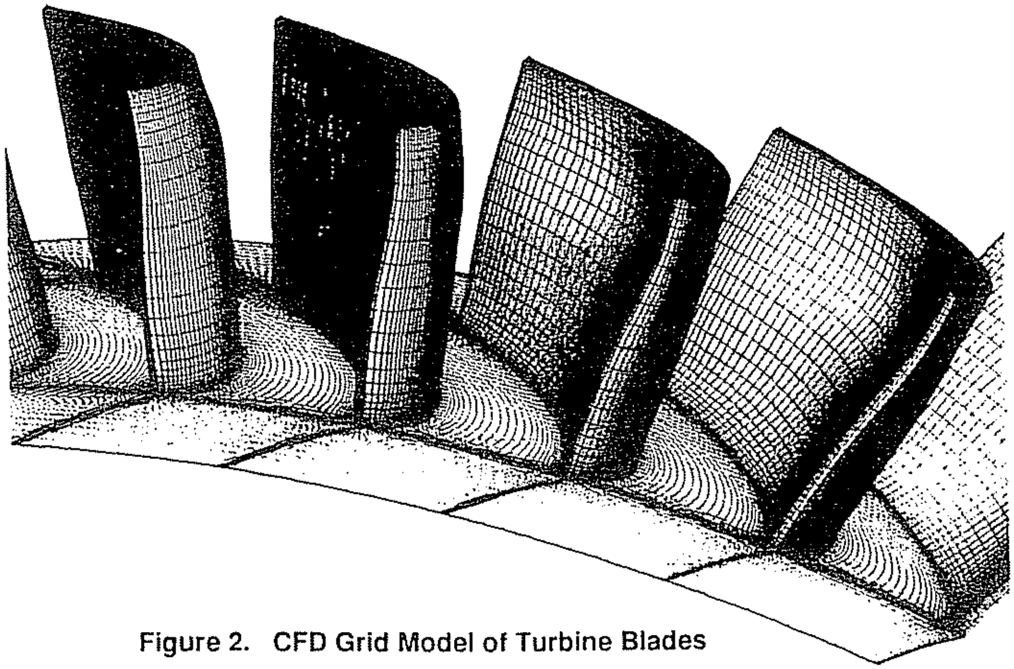

Figure 2. CFD Grid Model of Turbine Blades

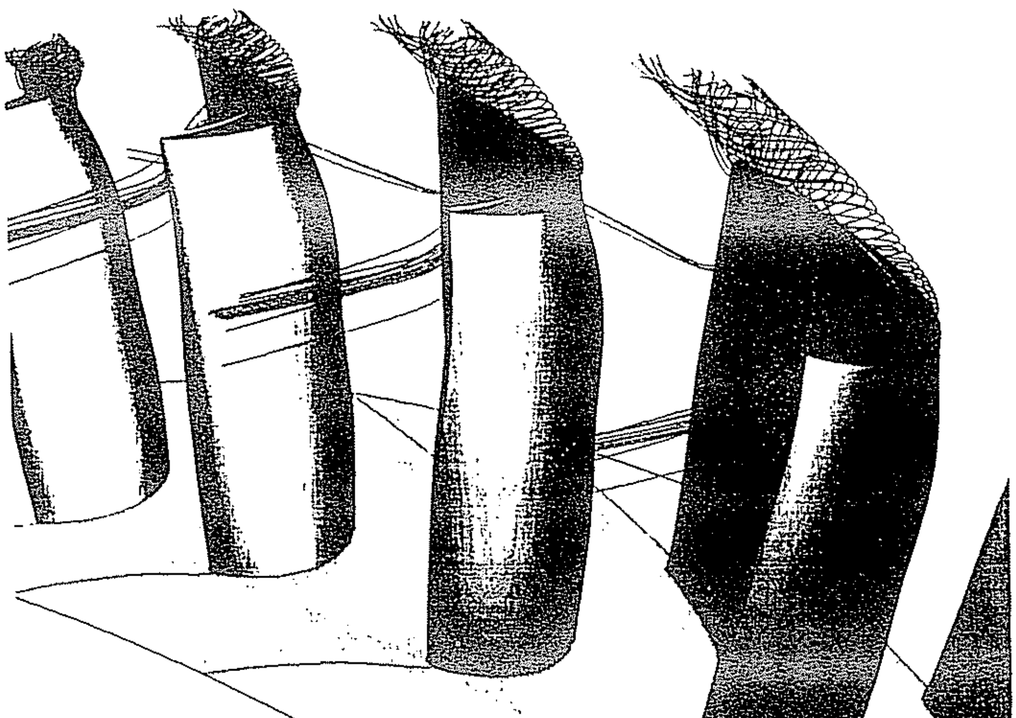

Figure 3. Vortices Along Turbine Blade Tips

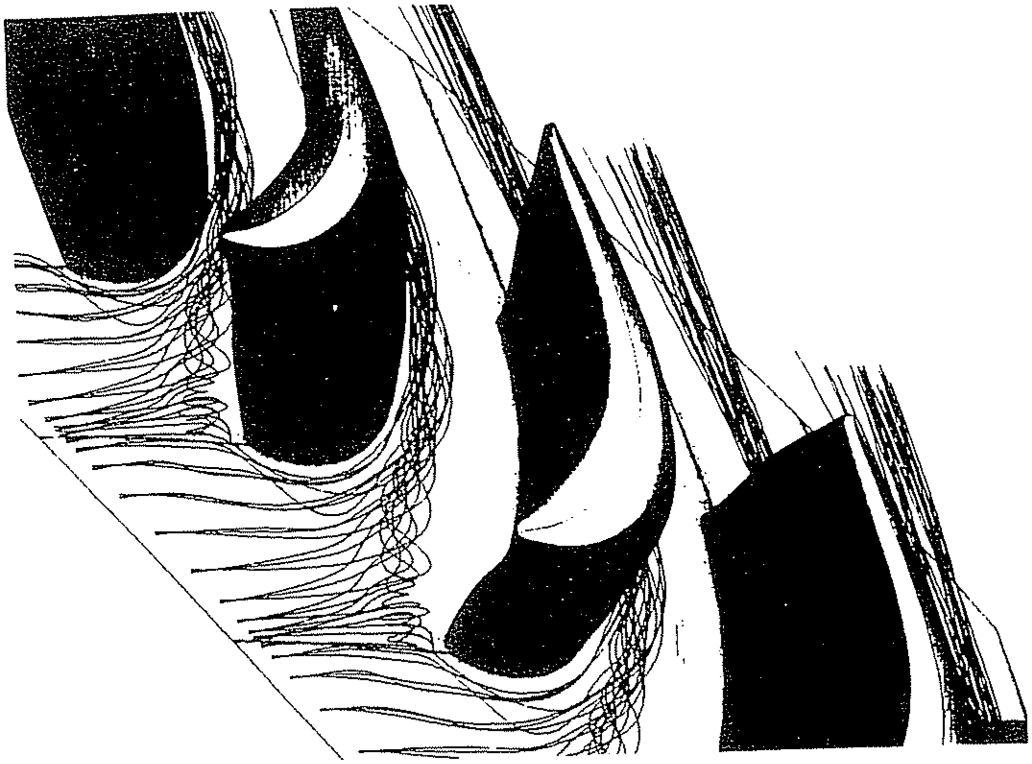

Figure 4. "Horseshoe" Vortices at Turbine Blade Hubs

Many other examples of CFD analyses may be found in the engineering literature. Naval architects use CFD to model the water flow around sailboats, submarines and large surface ships; automotive engineers use CFD to model the airflow around vehicles of all kinds; and aeronautical engineers use CFD to model the airflow around aircraft. The goal in most cases is to minimize the drag experienced by the object.

CFD vs. Experiment vs. Theory

Experimental fluid dynamics techniques were laid out in the eighteenth century, and theoretical fluid dynamics principles were developed in the eighteenth and nineteenth centuries. A significant contribution to fluid dynamics in the twentieth century is CFD, a methodology which complements the other two approaches.

CFD can be utilized in conjunction with theory and/or experiment. For example, if wind tunnel or tow tank tests are available for a certain object, a CFD model of the same object may be made and the results compared with experimental results. If the comparison is favorable, then the design parameters in the CFD model may be varied to determine relatively cheaply (in comparison to experiment) the effects of these changes on the flow characteristics of the problem.

There are also situations where the fluid flow is too complex for theory to handle, or when physical modeling becomes either technically or monetarily unfeasible. In these cases, CFD is the only recourse. Good analytical practice is to first develop a simple *baseline* model of the phenomena to be investigated for which test or theoretical results are available. Then, after the baseline model is checked out, the complicating features which make test or theory application impractical are added to the model, and the analysis is rerun. For example, an analyst interested in determining the drag force on an object due to accelerated motion in water might first evaluate the drag force on that object under steady-state motion, and compare the analysis results with known test data. If the comparison is acceptable, then the accelerated motion case could be run, and the analyst therefore could have more confidence in the accelerated motion results.

Potential Applications of CFD to Swimming

One significant difference between a swimmer and the turbine blades, ships and automobiles discussed earlier is that the shape of a swimmer is continually changing, making the problem of fluid flow around a swimmer very complex. CFD can accommodate problems with changing boundaries, but computers will have to get even faster and more powerful than they are now in order for a full-blown CFD analysis of an entire body undergoing swimming motions to be practical. However, at the rate computer speed and capacity are increasing, we will not have long to wait. In the meantime, CFD may still be used to significantly increase our knowledge of the fluid flow around swimmers in many ways. The following are just a few of the ways in which CFD may be applied to swimming:

1. Propulsive lift and drag of individual body parts may be evaluated. The optimum lift/drag force ratio at each point

in a swimmer's stroke may be determined individually for each swimmer.

2. The ideal shape for a swimmer's hand, arm, foot, or other body parts may be assessed.

3. The total drag force on a swimmer moving through the water may be determined. The relative contribution to this total force by form drag, skin friction drag, and wave drag may be determined.

4. Interference effects caused by one body part passing near another may be predicted (i.e., hand and arm passing near chest or beside thigh).

5. The effects of acceleration, deceleration and rotation on propulsive lift and drag may be evaluated.

6. Different forms of streamlining may be evaluated, and the optimum shape determined.

7. The effect of stroke depth on propulsion may be assessed.

8. The effect of underwater turbulence and waves on a swimmer's motion may be evaluated.

9. The effect of "dragging" off a swimmer in an adjacent lane may be quantified.

One of these topics, the effects of acceleration on propulsive hand drag, is addressed by the present paper. Although swimmers also use lift to generate propulsion, the focus of the present paper is on propulsive drag. Drag has been emphasized in this introductory paper on CFD to allow simple comparisons of analytical CFD results with known experimental drag force values. Propulsive lift is also critical in generating propulsion, and its exclusion in the present paper does not imply that lift is unimportant.

Review of Relevant Fluid Dynamic Principles

Before discussing the CFD analyses of accelerating flow, it is necessary for readers to understand several fluid dynamics definitions relevant to this study. Specifically of interest is the difference between steady and unsteady flow.

Steady Flow - When an object moves through a fluid at a constant velocity, the fluid motion is classified as steady flow. The properties at each point in the flow field do not change with time. Under these conditions, the drag coefficient, C_D, may be determined from experiment, and is related to the drag force, F_D, by the relationship:

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} \tag{1}$$

where: F_D is the drag force
ρ is the water density
V is the steady free stream velocity of the water relative to the object
A is the area created by projecting the object onto a plane perpendicular to the direction of flow

A similar equation may be written for the relationship between lift force and the lift coefficient. C_D is customarily presented as a function of Reynolds number (R) on a log-log graph. Reynolds number is a dimensionless parameter developed in 1863 by Osborn Reynolds to provide a criterion to determine the state of flow for problems where the relationship between inertia and viscous forces is important. Reynolds number is in fact the ratio of inertia forces to viscous forces and mathematically is defined as:

$$R = \frac{VL}{\nu} \tag{2}$$

where: V is the steady free stream velocity of the water relative to the object
L is a characteristic length descriptive of that object. Examples for an airplane, sphere, and a swimmer's hand would be, respectively, the wing chord length, the sphere diameter, and the width of the hand (thumb to little finger)
ν is the fluid kinematic viscosity

Unsteady Flow - When an object accelerates, decelerates, or changes its shape or orientation as it moves through a fluid, the flow will be unsteady: the properties at points in the flow field change with time. Schleihauf (18) and several subsequent researchers have used film or video cameras to determine the positions, orientations, and velocities of a swimmer's hand's during typical stroke cycles. Although the cyclic velocity patterns found in these studies varied somewhat from swimmer to swimmer and from study to study, all of them shared one characteristic: the motions of the hands were unsteady, with periods of acceleration and deceleration.

Over 200 years ago, Du Buat (7) investigated unsteady flow. He was followed by Bessel (3) in 1826 and most importantly, by Stokes (19) in 1851, who showed that the drag force on a sphere moving unsteadily within a fluid was dependent not only upon velocity, but also upon acceleration. Thirty years after Stokes' study, Boussinesq (4) and Basset (2) found that the drag force at a given time experienced by a sphere moving in an arbitrary unsteady manner depends on the entire history of its acceleration as well as the velocity and acceleration at that given time. Although these scientists used spheres in their studies, their conclusions apply equally to objects of other shapes. For swimmers this means that the propulsive drag and lift forces developed by a swimmer's hand at a given time are dependent not only upon the velocity at that time, but also the acceleration at that time and the acceleration history of the hand prior to that time. Hence, the drag equation shown in equation (1) is not valid for unsteady flow, and other methods must be used to calculate the drag force. Several methods are presented in the engineering literature to accomplish this, and we will briefly consider two of them.

Fluid Added Mass and the Drag Equation for Unsteady Flow

As a hand accelerates through the water, it experiences drag and lift forces from the water that are resistant to its motion, and imparts equal but opposite (in direction) forces to the water. Newton's second law is:

$$F = \frac{d}{dt} mv \qquad (3)$$

where: F is force
m is mass
v is velocity
$\frac{d}{dt}$ is the first derivative with respect to time

If we apply Newton's law to the hand motion, what is the mass m? The first answer that comes to mind is that m is the mass of the hand. But what other mass is involved? The answer is water. The next obvious question is: How much water? Some water is pushed by the hand and some flows around the hand. The additional mass of water pushed by the hand in accelerated flow is called the Fluid Added Mass or virtual mass, and scientists and engineers since Du Buat (7) have been analyzing and experimenting to determine the correct added mass for various objects moving in either air or water. As is probably obvious, added mass is much more significant in water than in air.

Added mass can be represented by a nondimensional Added Mass Factor (or Coefficient), k, which is determined experimentally and is defined as the added mass divided by the mass of fluid displaced by the object. Based upon the work by authors previously mentioned, as well as many others, it is possible to write a drag equation for unsteady flow, assuming a moving body is well beneath the surface (no wave making). If a body is accelerated through water which was initially at rest, its drag at time t is:

$$F_D = \tfrac{1}{2}\rho C_D V^2 A + k\rho\forall a \qquad (4)$$

where: F_D is the drag force
ρ is the fluid density
C_D is the drag coefficient for steady state flow
V is the instantaneous velocity at time t
A is the characteristic area of the body on which C_D is based
k is the added mass coefficient, also called the fluid inertial coefficient
$\forall$ is the characteristic volume of the body on which k is based (usually the volume of the object or the volume of a sphere that could contain the object)
a is the instantaneous acceleration at time t

The first term of Equation (4) is recognizable as the drag due to steady state motion. The second term represents the unsteady effects. It is interesting that Equation (4) provides a mathematical explanation as to why some coaches intuitively talk to their swimmers about "grabbing" as much water with their hands as possible. The more water that is "grabbed," the larger the added mass and the larger the propulsive drag.

Both C_D and k are determined experimentally, and it should be noted that the value of k is variable and depends upon the state of motion. Keulegan and Carpenter (11) have shown that when k is determined by oscillating (back and forth) acceleration tests rather than unidirectional (moving in one direction only) acceleration tests, it is also dependent upon the amplitude and oscillation period of the test apparatus. It is obvious that with so many variables involved, a significant testing program would be necessary to determine reliable added mass coefficients.

An alternative approach, valid only for unidirectionally accelerating objects, is less complicated. The acceleration effects on drag may be determined by calculating the Reynolds number and another non-dimensional number called the Acceleration Number, δ. The Acceleration Number is a dimensionless parameter developed by Iversen and Balent (10) who determined experimentally that it could be correlated to unsteady drag resistance. The acceleration number is defined as:

$$\delta = aL/V^2 \qquad (5)$$

where: a is the acceleration
L is the characteristic length
V is the velocity

The acceleration number concept will be used later in the present paper when CFD results from accelerated flow problems are presented.

Quasi-steady Flow: - Sometimes in order to simplify complex problems, the drag forces exerted on a body moving unsteadily within a fluid are *assumed* to be determined at any instant *only* by the velocity at that instant. This is the assumption of quasi-steady flow, and it allows drag and lift forces to be calculated using the equation for steady flow. It is an accurate assumption when the body's acceleration or deceleration is gentle. This assumption was first utilized by Schleihauf (18) in conjunction with experimental tests to determine hand drag and lift forces for hands at specific time points in a stroke cycle, and it is a valid approach as long as hand acceleration or deceleration are not significant.

The obvious question now is: are the motions of a swimmer's hands steady enough to calculate sufficiently accurate drag and lift forces assuming quasi-steady flow conditions, or should hand acceleration be taken into account? The CFD analyses discussed next were set up to answer that question.

CFD Applied to the Accelerated Motion of a Swimmer's Hand

Although swimmers have been urged to gradually accelerate their hands in the freestyle from the catch to the end of each armstroke by Maglischo (13) and Counsilman (6), the effect of this hand acceleration on drag and lift has not been quantified either experimentally or analytically. And although thousands of papers in engineering and scientific journals have investigated the unsteady flow effects on the drag and lift of a variety of shapes, few in the swimming community have taken advantage of this research. One notable exception are Pai and Hay (15), who experimentally determined the unsteady flow effects on the lift and drag of an oscillating cylinder, and compared their results with existing engineering solutions. Their experiments, applicable to the oscillating leg motion found in the flutter and dolphin kicks of swimmers, showed that the peak values for the lift and drag coefficients in the oscillating case were up to four times as much as those of the quasi-steady case. Another paper by Ungerechts (20) investigated the unsteady flow around an oscillating flexible model of a shark, whose undulating motion is similar in some ways to a swimmer's body during the butterfly.

Hand and arm accelerations are even more complicated than those of the legs. The path taken by the hands relative to the water is contorted and ever changing, and the hand undergoes significant amounts of both three-dimensional translational (every point on the hand moves in the same direction) and rotational (every point on the hand rotates about a single axis) acceleration. Although the effects of these translational and rotational accelerations are not independent, they may each be addressed separately *if* the other one is small. The present paper focuses only on translational accelerations, and assumes that rotational velocities or accelerations have a negligible effect on drag. Although this assumption is certainly *not* valid for all parts of an arm stroke, it is accurate for those portions of a stroke when arm and hand rotations are slow. The obvious question to ask is: How slow must the rotation be in order to be neglected? A study of unsteady high angle of attack aerodynamics literature shows this question is important, but a separate series of CFD analyses outside the scope of the present paper will be necessary to address it completely. However, some guidance may be taken from the study by Pai and Hay (15). Although their experiment was not set up to model a moving arm, it should be noted that when their test cylinder rotated at a velocity of 1 radian/sec the steady and unsteady drag and lift coefficients were very similar, while at a rotational velocity of 6.3 rad/sec the unsteady coefficients were significantly higher than the steady ones. No data was presented for rotational velocities between these two.

Analysis Approach

All the analyses of steady and accelerated flow discussed in the present paper are aimed at modeling either the insweep or upsweep of a freestyle stroke, and all the velocities and accelerations in the CFD models are within or near the range of typical hand velocities and accelerations generated by freestyle swimmers during those sweeps. As mentioned above, the rotational effects during these sweeps are neglected.

Engineers in industry, when faced with a difficult problem, often first solve a similar or simplified problem to which they know the answer. Then, they add one complex feature to the problem and solve it again. Then they add another complex feature and solve it once more. They repeat this process over and over until eventually their simple problem has evolved into the complex problem they were first given to solve. This procedure has two important advantages over proceeding directly to the complex problem: it gives the engineer confidence in the accuracy of the answers, and it reveals how each added complexity individually affects the final answers. And if some of the complex features are shown to not significantly affect the final answers, then they can be ignored in the future without sacrificing the accuracy of the answers, thus saving time and money.

The problem of determining the affects of acceleration on hand propulsive forces has been approached in the same manner. Four CFD models of varying complexity will be used in the process. They are listed below, beginning with the simplest and ending with the most complex. The present paper reports on the results from the first two models. Modeling of the last two models is in progress, and results will be reported in a future paper.

The Four Levels of Model Complexity

Level 1. Disk in steady flow normal to surface
Level 2. Disk in accelerated flow normal to surface
Level 3. 3D hand model in steady flow at various angles of attack
Level 4. 3D hand model in accelerating flow at various angles of attack

Level 1 Model- A simple way to represent a hand moving through the water is to model it as a disk having the same area as a typical hand (0.018 m^2). Although the drag coefficient of a disk is not exactly the same as a hand, a disk was chosen for initial modeling studies because the drag coefficient of a disk in steady flow normal to its surface is known to be a constant 1.17 for flows with Reynolds numbers greater than about 1500 [Hoerner (9)]. Thus, the correct answer to the first problem is known, and the model can be validated by checking the results with the known solution. The lift force is zero.

Level 2 Model- A disk is also a good choice for the second level of modeling complexity which involves accelerated flow. Since the Reynolds number of a disk moving at the velocities of the accelerating portions of a stroke cycle is significantly greater than 1500, Reynolds number effects will be negligible and all the differences between steady-state drag and accelerated flow drag on the disk may clearly be attributed to acceleration affects. The lift force is zero.

Level 1 and Level 2 Models Combined- It is obvious that a swimmer's hand is shaped differently than a disk and that a swimmer's hand changes its angle of attack as it moves through the pull. How then are the disk drag forces obtained in the Level 1 and 2 Models relevant to swimming? The results from these analyses, shown later in the present paper, will allow the reader to calculate, using a disk, a percentage change in propulsive drag force caused by accelerated motion. Then, knowing from the published literature how a hand accelerates during a stroke, a simple first approximation of the drag force generated by a swimmer's hand undergoing accelerated motion may be found as follows:

1. The propulsive drag force of a hand using quasi-steady methods may be calculated using the known steady state drag coefficients of a hand from published papers such as Schleihauf(18)

2. This quasi-steady hand drag force is multiplied by the percentage increase in propulsive drag (due to acceleration) experienced by a disk undergoing the same acceleration and velocity as the hand. This percentage increase may be determined from the results of the present paper.

This simple technique uses not the numerical value of the disk drag, but the ratio of acceleration drag to quasi-steady drag of the disk to modify the quasi-steady drag of the hand to account for acceleration. This method assumes that the percentage change in drag due to acceleration will be the same for the disk and the hand. While this assumption may not be absolute, but rather an estimate, it does provide a first level approximate way to predict the affects of acceleration on drag. Additional CFD modeling of actual hands and arms, presently underway and to be published in the future, will provide a more accurate evaluation of the acceleration effect. However, the approach presented in the present paper still represents an improvement on the present way of calculating drag (quasi-steady flow), which cannot account for some of the effects of unsteady flow. Thus, the reader may approximately quantify the effects of accelerated hand motion on the propulsive drag force of a hand during the freestyle insweep or upsweep.

Level 3 and Level 4 Models- The models of actual hands at these levels will be used to investigate lift as well as drag, and the angle of attack and Reynolds number will be additional variables to consider. These studies are underway, and the results will be reported in a future paper.

Computer Software and Hardware

All CFD analyses in this study were performed with FLUENT, a commercial and widely available computer program for modeling fluid flow, heat transfer, and chemical reactions. All analyses were performed using a Silicon Graphics Workstation. For readers who may be familiar with advanced numerical computer techniques and fluid dynamics, additional technical details about FLUENT and the turbulence models used in these analyses are given in the Appendix.

Analysis Parameters

All fluid properties were taken for a water temperature of 80 degrees Fahrenheit (22.6 degrees C). At this temperature the density of water is 996.6 kg/m^3 and the viscosity is 8.571 x 10^{-4} kg/m-sec. Incompressible flow (density is constant) was assumed. This assumption is valid except at the very beginning of a stroke when bubbles are trapped by the hand.

Another assumption in all the analyses is that the hand (or object considered) is far enough below the surface to not be influenced by the surface, eliminating any complexities due to wave drag. This assumption is valid except at the very beginning and end of the stroke when the hand is close to the water surface. As mentioned previously, in all models only translational acceleration was allowed, although the shape and magnitude of the acceleration curve was varied.

A disk moving along an axis normal to its surface (angle of attack = 90 degrees) may be classified as an axisymmetric problem (the disk is symmetrical about this axis). Such problems may be solved with a 2D planar CFD grid as long as the CFD program is instructed that the planar grid actually represents a 3D axisymmetric problem. This greatly reduces the problem size and solution time on the computer. The 2D CFD grid model of the disk and the surrounding water is shown in Figures 5 and 6. The x axis is the axis of symmetry, and the entire problem would be represented by "sweeping" the 2D planar grid 360 degrees about the x axis to make a 3D model. The planar grid is 87 cells long and 62 cells wide, with a length of 2 meters and width of 1 meter. The radius of the disk shown in the figures is 0.0757 meters and its width of 0.01514 meters. This radius swept through a 360 degrees would give an area of 0.018 m^2, the same area as a typical hand. Coarser and finer grids were also tried, but the grid size shown is the one which gave sufficiently accurate answers in the shortest computing time.

A variety of steady and accelerated flow analyses were performed using this grid. Variables in the analyses were the initial and final velocities, the time and distance of motion, and the shape of the acceleration function. As demonstrated in Figure 7, three basic kinds of acceleration functions were used: constant acceleration, sinusoidally increasing acceleration, and sinusoidally decreasing acceleration. Although the amplitude and time duration of the stroke may change from analysis to analysis, the basic shape of these three acceleration curves remains the same. The velocity curves corresponding to these acceleration functions are shown in Figure 8. All accelerated flow analyses were preceded by a steady-state analysis with a velocity equal to the initial velocity of the accelerated flow analysis. Velocities and accelerations, always given with respect to the water, were chosen in the range of those found during the insweep or upsweep of a freestyle stroke.

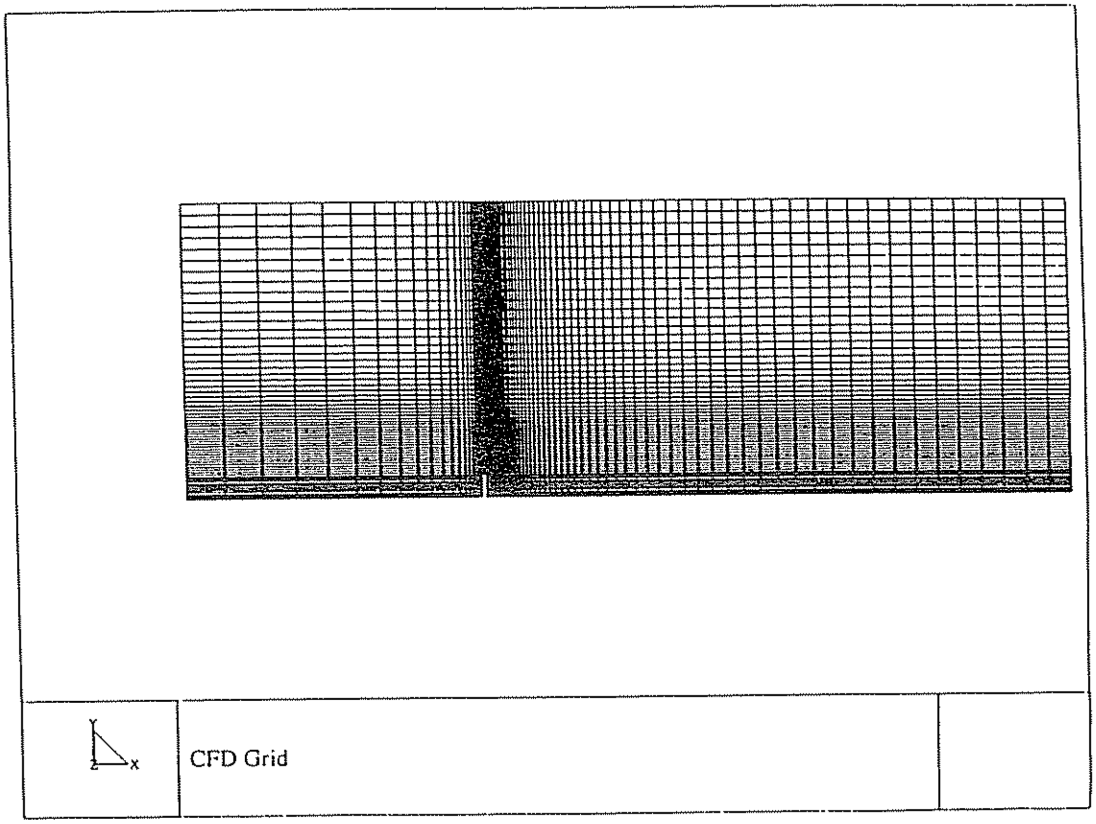

Figure 5. CFD Grid for Circular Disk Analysis

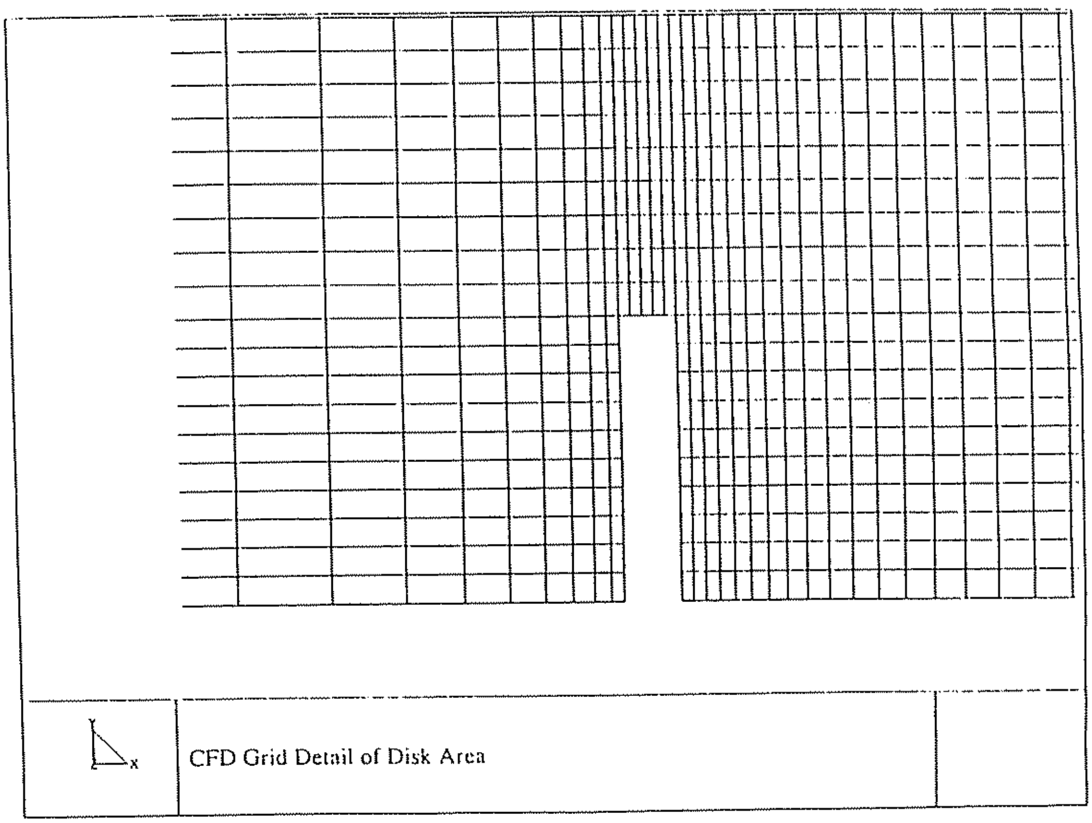

Figure 6. CFD Grid Detail of Circular Disk Area

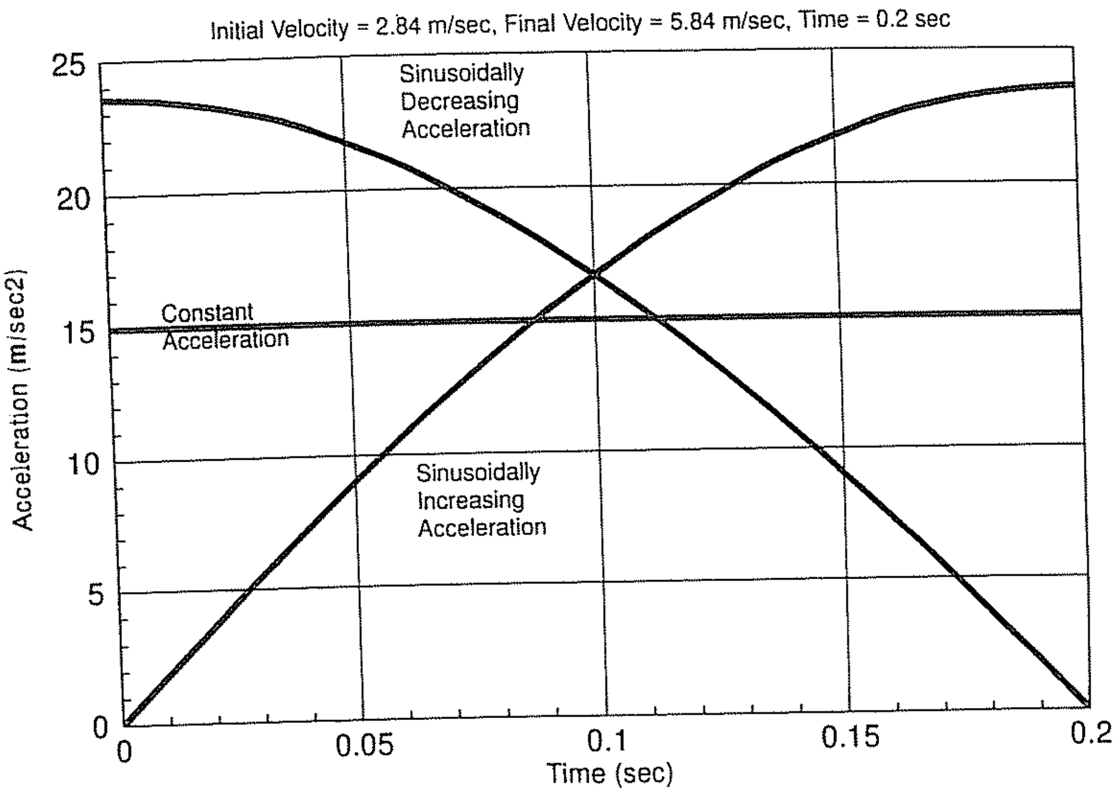

Figure 7. Acceleration Functions

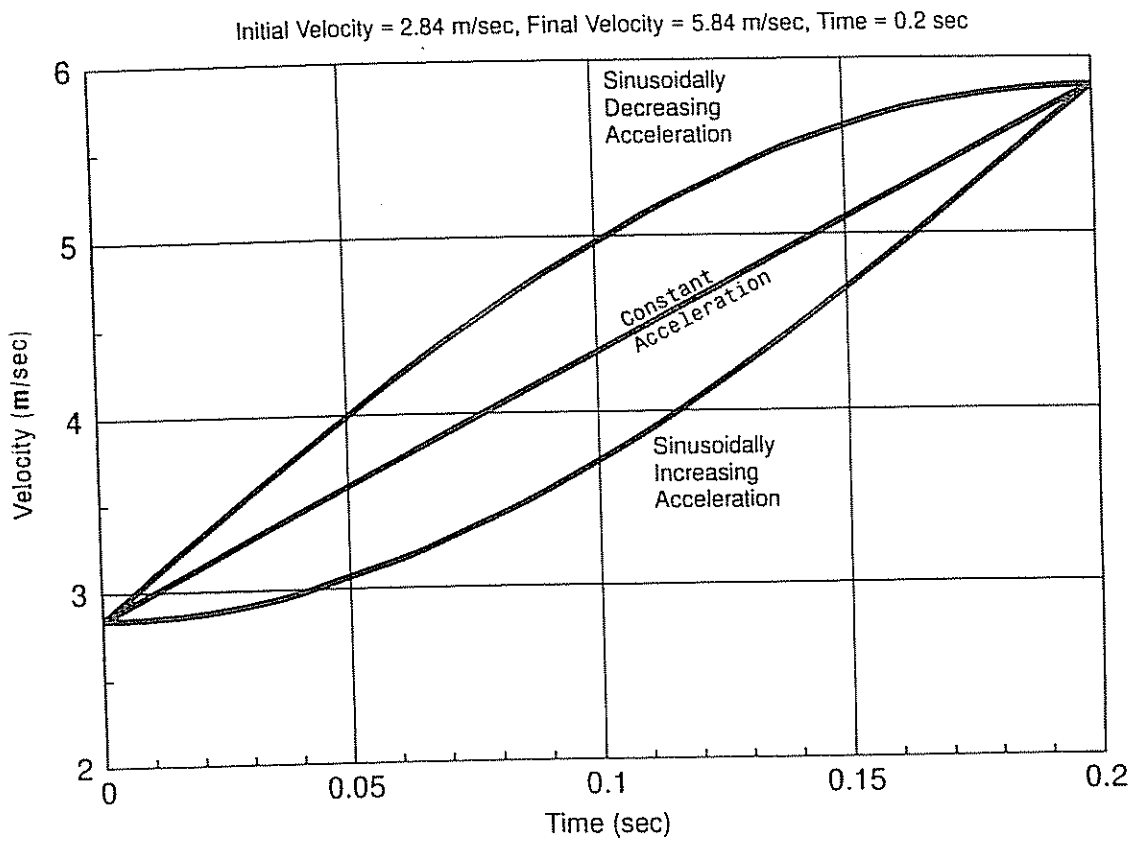

Figure 8. Velocity Curves for the Acceleration Functions

The various flow analysis cases and their variables are presented in Table 1. They are divided into two groups based upon their variables. Group I cases were set up to investigate how the shape of the acceleration function affects the propulsive drag. Initial and final velocities of the analyses were kept constant at 2.84 m/sec and 5.84 m/sec, respectively, while the acceleration functions and the time of acceleration were allowed to change. In the Group II cases, the initial and final velocities as well as accelerations were varied, but were chosen such that the distance traveled by the disk (stroke length) always came out to be 0.58 m. The acceleration in each Group II case was a constant acceleration. Sinusoidally varying accelerations were not considered in Group II.

known solution. The drag force calculated by the model was 84.8 Newtons and the actual value is 84.6 Newtons. This amount of error (0.2%) is well within the generally accepted 5% error for simple CFD problems and up to 10% for complex problems. All the rest of the steady-state solutions were also within the acceptable 5% error band. The important result from each CFD analysis is the drag force on the disk. FLUENT supplies this information for both steady and unsteady analyses. A single value is obtained for steady analyses and a time history of the drag force may be made for unsteady analyses. Also available as output is a plot of the flow field, which helps the analyst to verify that the problem has been correctly solved. Figures 9 and 10 show vector plots

Table 1. CFD Flow Analysis Cases

Group	Subgroup	Case No.	Acceleration Function (m/sec2)	Acceleration Time (sec)	Initial Velocity (m/sec)	Final Velocity (m/sec)
I	A	1	Constant	0.2	2.84	5.84
		2	Constant	0.266	2.84	5.84
		3	Constant	0.4	2.84	5.84
	B	1	Sinusoidal Increase	0.2	2.84	5.84
		2	Sinusoidal Increase	0.266	2.84	5.84
		3	Sinusoidal Increase	0.4	2.84	5.84
	C	1	Sinusoidal Decrease	0.2	2.84	5.84
		2	Sinusoidal Decrease	0.266	2.84	5.84
		3	Sinusoidal Decrease	0.4	2.84	5.84

Group I cases were set up to investigate how the shape of the acceleration function affects the propulsive drag. Initial and final velocities were held constant in all Group I cases.

Group	Subgroup	Case No.	Acceleration Function (m/sec2)	Distance Traveled (m)	Initial Velocity (m/sec)	Final Velocity (m/sec)
II	A	1	Constant 8.6	0.58	1.7	3.6
		2	Constant 15.25	0.58	2.43	4.87
		3	Constant 17.91	0.58	1.7	4.87
		4	Constant 6.20	0.58	2.43	3.6
		5	Constant 1.66	0.58	1.7	2.2
		6	Constant 4.96	0.58	1.7	2.94

Group II cases were set up with a constant stroke length (distance traveled) and a constant acceleration *function*. Initial and final velocities and the acceleration rate were allowed to vary from case to case.

Results

Using the previous Equation (4) and the known disk steady-state drag coefficient of 1.17, the actual force for steady state flow may be obtained as a function of velocity. To verify the correctness of the modeling and solution procedure, a steady-state case was run for a velocity of 2.84 m/sec (in the range of freestyle hand velocities found in the literature) and the drag force obtained was compared with this

of the flow field around the disk for the steady-state case above. The length of the vectors in these plots is proportional to the velocity at the vector location. Another method to visualize flow is with streaklines, as shown in Figure 11. Each of these lines represents the path a fluid "particle" would make as it "streaks" by the disk. The results have been "mirrored" about the y=0 line of symmetry so that the whole flow field may be seen.

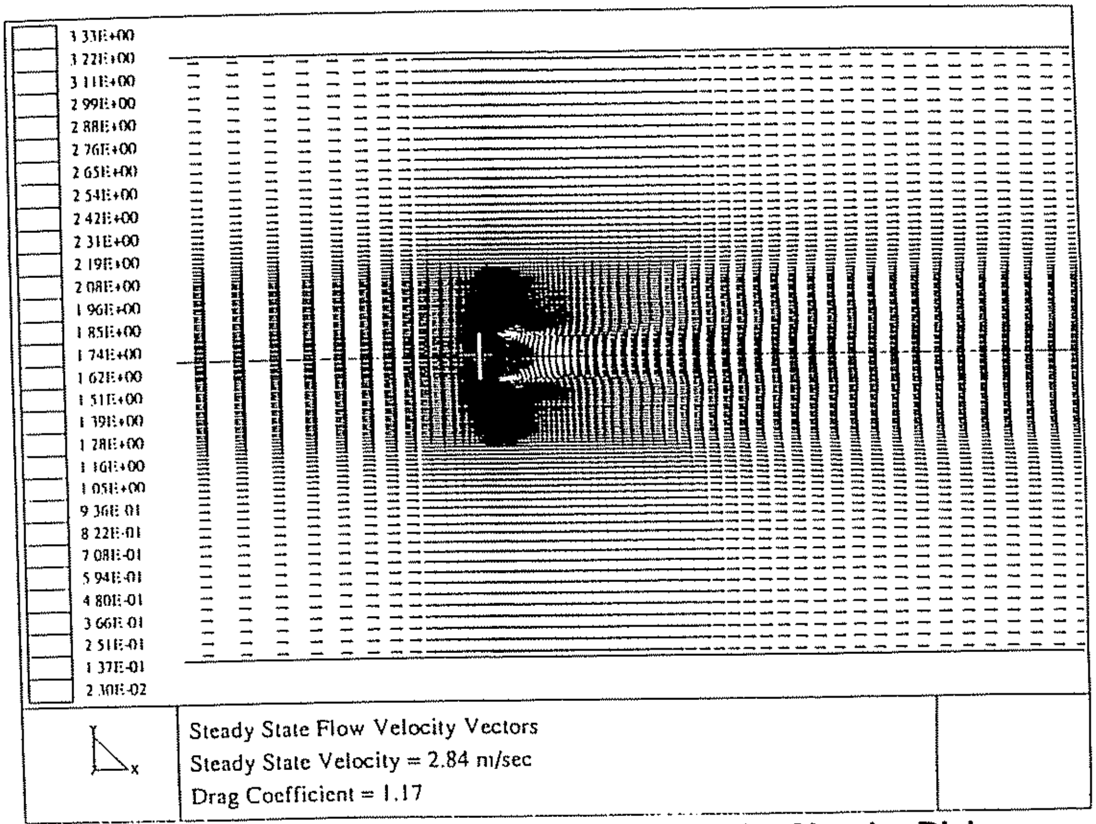

Figure 9. Vector Plot of Fluid Flow Around a Circular Disk

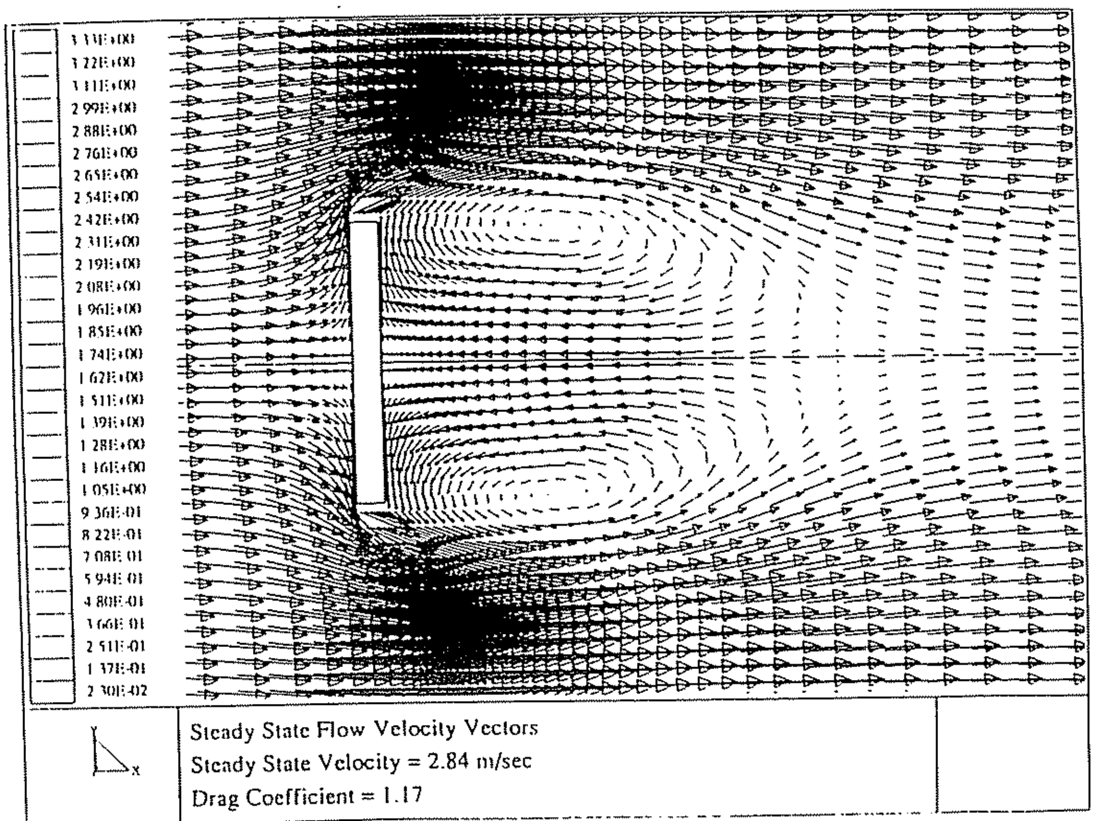

Figure 10. Vector Plot Detail of Fluid Flow Around a Circular Disk

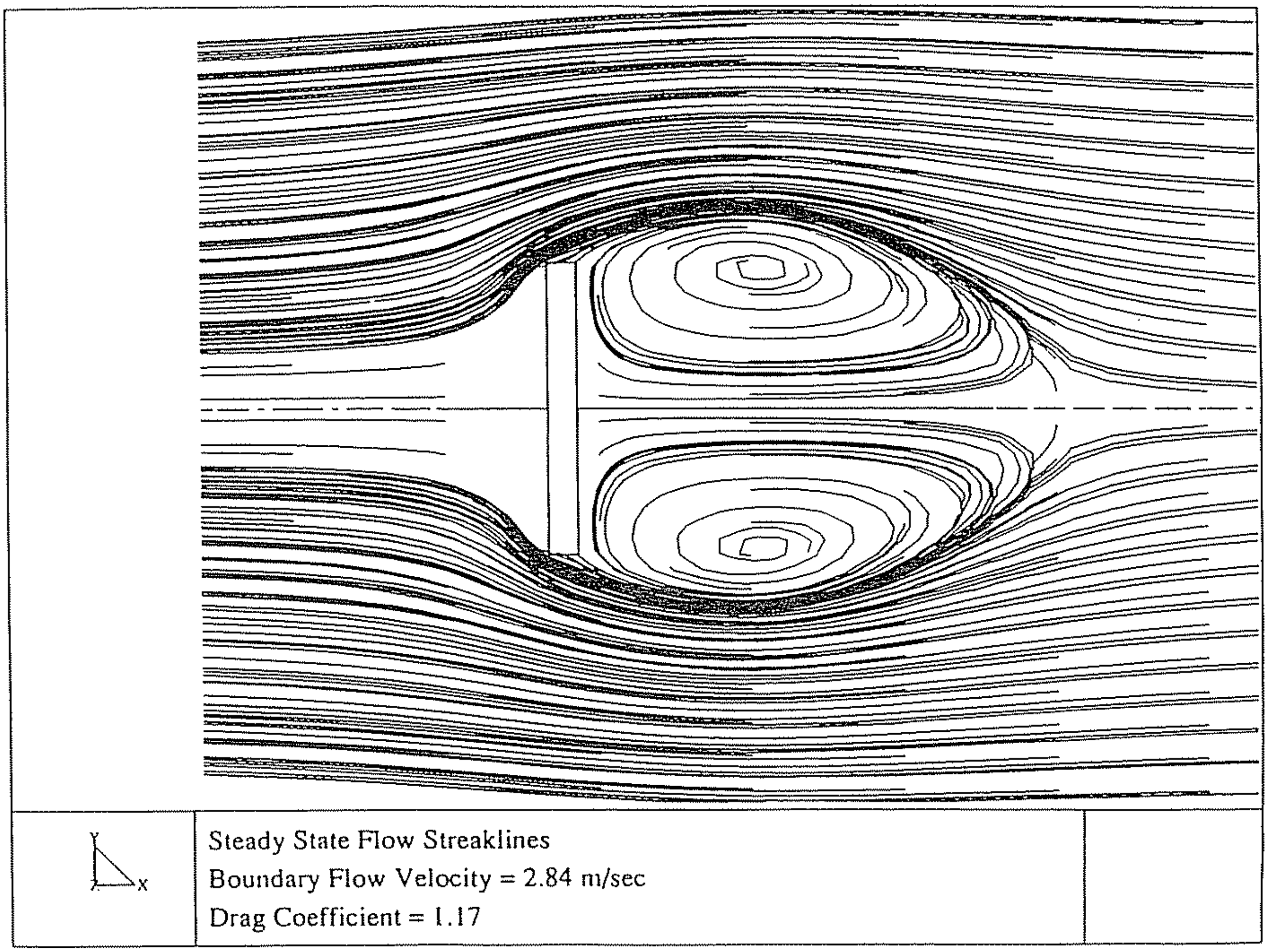

Figure 11. Streakline Plot of Fluid Flow Around a Circular Disk

Group I Results

The results of the CFD analyses for the Group I cases are shown in Figures 12 through 14, where the drag force on the disk vs. time is plotted for the three types of acceleration functions and for various stroke durations. For comparison purposes, the time-averaged drag forces assuming quasi-steady flow are also plotted on the same graphs. The average drag forces during the duration of the "pull" are displayed in Table 2 and compared with the values using the quasi-steady method of calculation. Also, Figure 15 compares the drag force time history for the three constant acceleration cases only.

Group II Results

The time history plots of drag force from the CFD analyses of the Group II cases are plotted in Figure 16. The average drag forces for these cases are compared in Table 3 with those calculated using the quasi-steady method. Then, in Figure 17, a plot of $F/\rho\forall A$ vs. the acceleration number aL/V^2 is presented.

where: F = Average drag force during the time of acceleration
- ρ = Fluid density
- $\forall$ = Characteristic volume of the disk (in this case the volume of the disk was used as the characteristic volume)
- a = Acceleration
- L = Characteristic length of the disk (in this case the disk diameter)
- V = Average velocity during the time of acceleration

Figure 17 provides a method to accurately calculate the drag forces in a constantly accelerating flow if the initial and final velocities are known. If Reynolds number were important for a disk, then there would be a separate curve for each Reynolds number under consideration. It should be noted that both variables in Figure 17 are nondimensional (all the units cancel each other out, making the variables unitless).

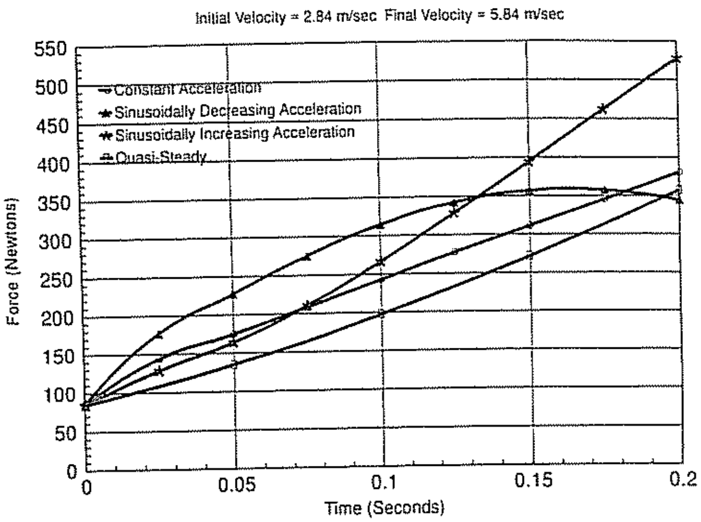

Figure 12. Drag Force on Accelerated Disk (Acceleration Time = 0.2 sec)

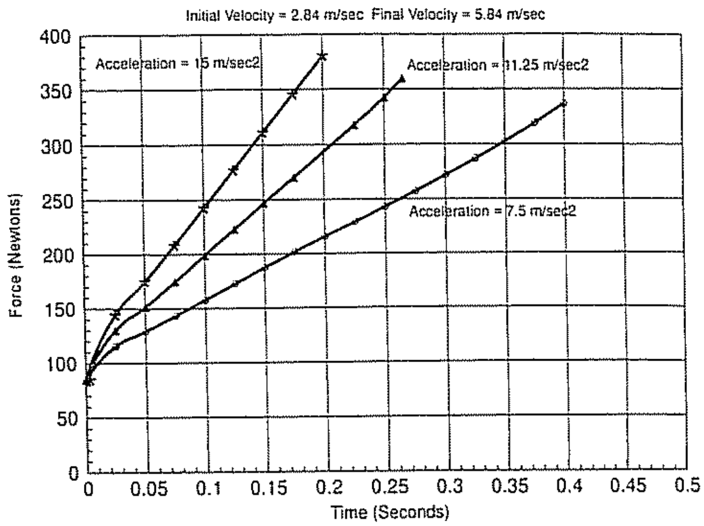

Figure 15. Drag Force on a Disk under Constant Acceleration

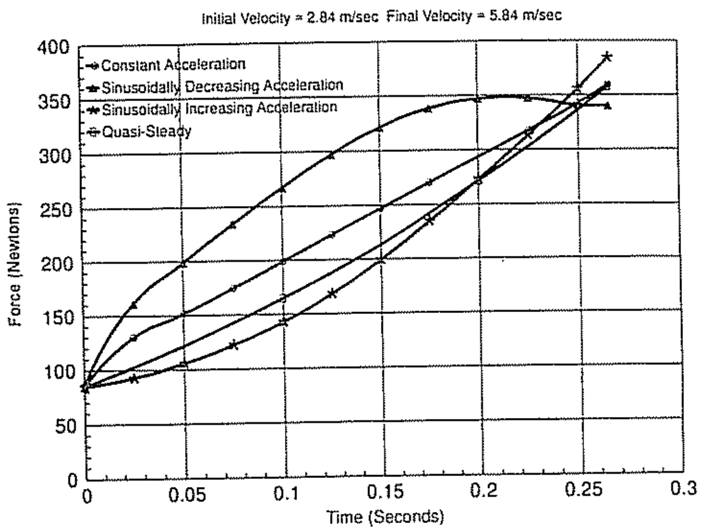

Figure 13. Drag Force on Accelerated Disk (Acceleration Time 0.266 sec)

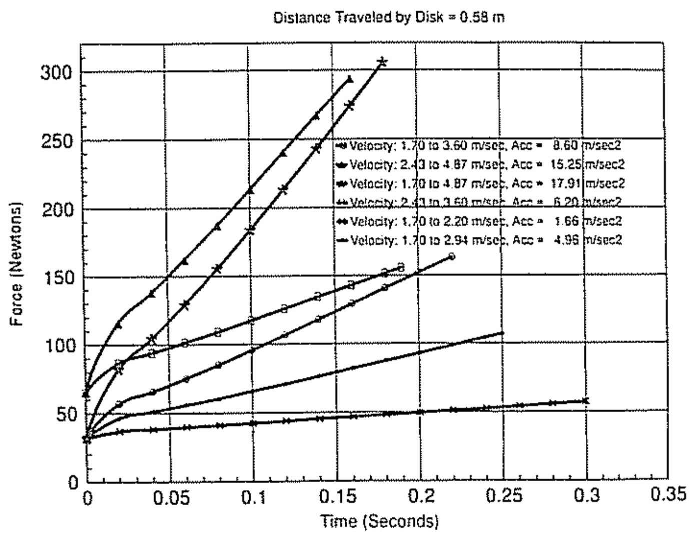

Figure 16. Drag Force on Disk under Constant Acceleration

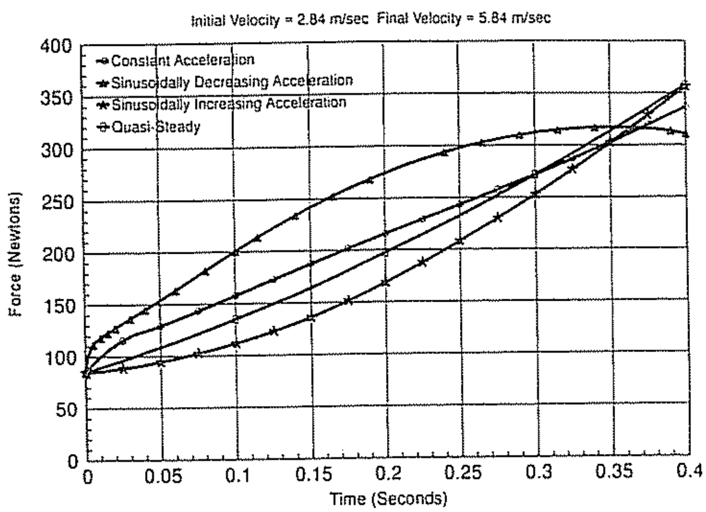

Figure 14. Drag Force on Accelerated Disk (Acceleration Time = 0.4 sec)

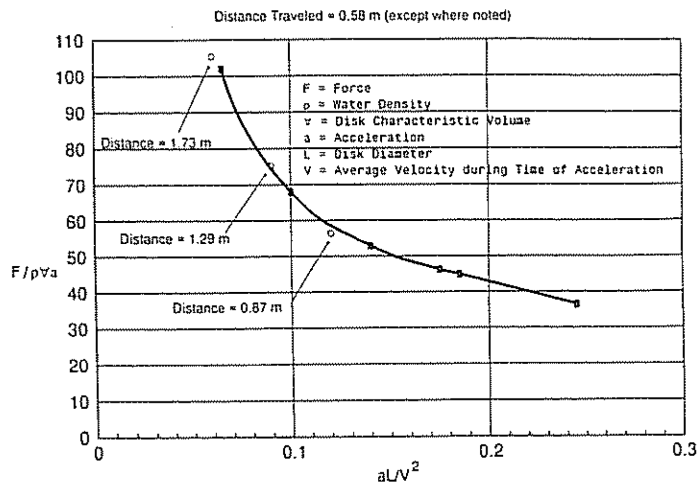

Figure 17. Drag Force Relationships for Disk under Constant Acceleration

Discussion

Discussion of Group I Results

The results from the Group I cases shown in Figures 12-15 and in Table 2 are important not for what they show, but instead for what they don't show: they don't show an acceleration pattern which maximizes propulsive drag force in all situations. In other words, the calculated ratio of drag under accelerated flow to drag under quasi-steady flow shows that it is better to start out with a large acceleration and decrease it in many of the cases, but in another case (IB1) it is equally effective to do just the opposite. And in fact, if the acceleration time were decreased to less than 0.2 sec, it is likely that a sinusoidally increasing acceleration would provide the largest propulsive force. Of course, to determine the "optimum" rate of acceleration and the "best" stroke, the biomechanics of motion and the internal energy and power used to accomplish that acceleration should ideally also be considered.

However, the most important fact obtained from the Group I analyses is that for a given acceleration function type, the propulsive drag force increases beyond the quasi-steady values as the acceleration increases, except for cases IB2 and IB3, where a unrealistic zero initial acceleration rate is never quite recovered from. In some cases, as shown in Table 2, the increase in drag above quasi-steady values approaches 40%.

Table 2. CFD Flow Analysis Group I Results

Group	Sub-group	Case No.	Acceleration Function	Acceleration Time (sec)	Initial Velocity (m/sec)	Final Velocity (m/sec)	Average Drag Force (Newtons)	Force Ratio: Acc. Drag /Q-Steady Drag
I	A	1	Constant	0.2	2.84	5.84	242	1.17
		2	Constant	0.266	2.84	5.84	230	1.12
		3	Constant	0.4	2.84	5.84	215	1.04
	B	1	Sinusoidal Increase	0.2	2.84	5.84	282	1.38
		2	Sinusoidal Increase	0.266	2.84	5.84	200	0.97
		3	Sinusoidal Increase	0.4	2.84	5.84	189	0.91
	C	1	Sinusoidal Decrease	0.2	2.84	5.84	283	1.37
		2	Sinusoidal Decrease	0.266	2.84	5.84	254	1.23
		3	Sinusoidal Decrease	0.4	2.84	5.84	251	1.21
Quasi-Steady Case			Interpolated	0.2	2.84	5.84	206	NA
Quasi-Steady Case			Interpolated	0.266	2.84	5.84	206	NA
Quasi-Steady Case			Interpolated	0.4	2.84	5.84	206	NA

Group I average drag forces during the duration of an accelerated "pull" are compared with the time-averaged drag forces calculated using a quasi-steady method of calculation.

Discussion of Group II Results

The cases in Group II all have constant but different acceleration functions as shown in Table 3 and Figure 16. Velocities, accelerations, and stroke duration were chosen such that the distance traveled during each stroke was 0.58 meters. Looking at the ratios of accelerated drag force to quasi-steady drag force in Table 3, it is obvious that neither the velocities nor the accelerations alone can determine the effect of acceleration upon drag force. However, if the time-averaged velocity during the acceleration period is used in the acceleration number, aL/V^2, and plotted vs. the average drag force during the same period nondimensionalized by $\rho \forall a$, the curve in Figure 17 is established. In fact, even the three constant acceleration cases in Group I with stroke distances different than 0.58 m also fall along this curve. This plot is useful because it allows the calculation of drag forces for constant acceleration flow given the initial and ending velocity values and the disk geometry. Both axes are nondimensional, and the curve may be used with disks of different diameters, but should not be used with a different type of acceleration function. If the disk was replaced with an object with more rounded edges (such as a hand), a plot of similar form but with different values could be made, but it would be valid only for a certain Reynolds number. A family of curves for different Reynolds numbers would be necessary to totally characterize the behavior of an object with rounded edges.

As with Group I, the propulsive drag force is increased up to 40% beyond the quasi-steady drag values within the range of variables considered.

Table 3. CFD Flow Analysis Group II Results

Group	Sub-group	Case No.	Acceleration Function (m/sec2)	Distance Traveled (m)	Initial Velocity (m/sec)	Final Velocity (m/sec)	Average Acc Drag Force (Newtons)	Average Q-Steady Drag Force (Newtons)	Average Force Ratio: Acc. Drag/ Q-Steady Drag
II	A	1	Constant 8.6	0.58	1.7	3.6	105	77	1.36
		2	Constant 15.25	0.58	2.43	4.87	190	145	1.31
		3	Constant 17.91	0.58	1.7	4.87	178	124	1.43
		4	Constant 6.20	0.58	2.43	3.6	113	97	1.16
		5	Constant 1.66	0.58	1.7	2.2	46	40	1.15
		6	Constant 4.96	0.58	1.7	2.94	74	58	1.27

Group II average drag forces during the duration of an accelerated "pull" are compared with the time-averaged drag forces calculated using the quasi-steady method of calculation.

Limitations of the Study and Possible Resolutions

As in all studies, it is important to realize the limitations of the evaluations that have been performed. Some of them have already been mentioned, and some have not. Some of them may affect the final answers, and some may not. Additional studies will be necessary in some cases to determine their effects. A summary of the different limitations and possible actions to resolve them is given below.

1. Initial studies have been performed using disks, rather than actual CFD models of hands. However, the principles of fluid dynamics which increase the drag on a disk in accelerated flow also apply (with adjustments for changes in Reynolds number) to a hand or any other shape. Therefore, an increase in the propulsive drag of a hand due to acceleration would also be expected. Studies are presently underway to verify this, and the results will be reported in a future paper.

2. The effects of initial water turbulence have not been addressed. Future analyses should at some point include these as variables to determine their impact on drag. This limitation could be addressed in the second phase of this study with actual hand models.

3. During the insweep and upsweep of a swimmer's freestyle, the hand rotates as well as translates. This study investigated drag force for angles of attack only equal to 90 degrees, and ignored the effects of rotation. Other angles of attack can and will be evaluated by changing the geometry of the grid. Although the model size significantly increases because the axisymmetric option may no longer be used, resulting in a fully three-dimensional and much larger grid, the problem is still manageable. The rotation of the hand during the stroke is a more difficult phenomena to sort out. In this initial study, rotation was ignored. Analytically, the modeling of both translation and rotation is a complicated problem, but with significant computer time, it *is* possible to solve. The first step would be to examine steady translation with a constant rate of rotation. Then, if necessary, analyses with accelerating hand translation and/or unsteady hand rotation could be made.

4. In the present paper we have interchangeably spoken of the disk moving through the water and the water moving past the disk. In steady flow, the drag experienced by the disk is the same either way. This may be called the Principle of Relative Motion. This principle is very useful, because it allows us to discuss our problem in whatever frame of reference is the most convenient. However, there is a serious limitation to this principle: it is valid only for steady flow.

For unsteady flow, the force on a stationary body in an accelerating fluid is greater than the drag force on a body accelerating through a initially stationary fluid by a factor called the horizontal buoyancy force. The horizontal buoyancy force, so named because it is brought about by a horizontal pressure gradient, may be approximated by $\rho \forall a$, where ρ is the fluid density, $\forall$ is the characteristic volume of the body, and a is the acceleration of the body. Standard CFD modeling techniques assume objects are stationary and the fluid is moving. In our case, the swimmer is moving and the water is stationary. Therefore, the values from our accelerated flow analyses need to be reduced by this factor, which in most cases is very small. For example, from Case II-A-1 with an acceleration of 8.6 m/sec2, using the volume of the disk as the characteristic volume, $\rho \forall a$ is equal to 2.3 Newtons, or 8% of the difference between the accelerated flow drag of 105 Newtons and the quasi-steady flow drag of 77 Newtons. There is a way to analyze our flow problems with a moving grid, but it is computationally more time-consuming and expensive. However, at some point in the future, this will be done.

5. Another limitation, perhaps less obvious than some of the others, is that our evaluation starts at a point in the middle of a stroke cycle, either at the beginning of the freestyle insweep or the freestyle upsweep. Yet, as was pointed out earlier, Boussinesq (4), in 1885 proved that the drag force at a given time experienced by a moving object in an arbitrary unsteady manner depends on the entire history of its acceleration, not just the velocity and acceleration at that given time. Therefore, to be totally accurate, the stroke should be evaluated from water entry to water exit. This would be extremely difficult and computationally intensive, but it would be the ultimate definitive CFD evaluation of the stroke. Before this type of extremely complex evaluation is attempted, there are many simpler but still useful analyses that should be conducted.

Summary

The mechanics and fluid dynamics of swimming are extremely complex, providing difficult problems that need "hi-tech" methods to solve them. Computational Fluid Dynamics (CFD) has been introduced as an analytical tool useful in modeling complex fluid flow problems using computers. A simple disk whose surface is normal to steady and accelerated fluid flow has been analytically evaluated to demonstrate the power of CFD, and to increase our knowledge about drag in accelerated flow, a topic which has not been sufficiently addressed in the swimming literature. The following observations and conclusions are noteworthy:

1. Although the CFD analyses presented in the present paper provided only first level approximations of the affects of acceleration on hand propulsive drag, the results clearly showed that acceleration may increase propulsive drag above quasi-steady values by as much as 40%. Coaches should encourage their swimmers to accelerate their hands from start to finish of their freestyle strokes, especially during the insweep and upsweep. This is what Counsilman intuitively advised many years ago, and now we have scientific proof that this is indeed the correct approach.

2. The added mass concept summarized by Equation (4) provides a mathematical explanation as to why some coaches intuitively talk to their swimmers about "grabbing" as much water with their hands as possible. The more water that is grabbed, the larger the added mass, and the larger the propulsive drag and lift.

3. The propulsive drag and lift forces developed by a swimmer's hand (or any body part) at a given time are dependent not only upon the size, orientation, shape, and velocity of a swimmer's hand at that time, but also upon the acceleration at that time *and* upon the acceleration history of the hand prior to that time.

4. The Principle of Relative Motion is only valid for steady flow. For unsteady flow, the force on a stationary body in an accelerating fluid is greater than the force on a body accelerating through a stationary fluid by a factor called the horizontal buoyancy force. In a swimming flume, although the water velocity may be held constant, a swimmer's arms and legs are accelerating and decelerating. Thus, the horizontal buoyancy force is one factor that may account for a swimmer's flume performance being different from his or her pool performance.

The analyses presented in the present paper represent the first half of an ongoing study evaluating the acceleration affects on hand propulsive drag. The disk analyses have shown that acceleration can significantly affect drag force calculations, and that more complex CFD models of arms or hands are worth building and analyzing. The authors have work in progress doing just that, where Reynolds number and angle of attack are additional variables being considered. As additional and more complex analyses are performed, a database of drag and lift coefficients for use in unsteady flow conditions can be developed. This information will be useful in evaluating stroke technique and recommending methods for stroke technique improvement.

Practical Application

Although the second half of this ongoing study will develop more accurate results, we still may estimate the increase in drag force on a hand in accelerated flow with the aid of Figure 17. The following example will demonstrate the process.

Use Figure 17 to Estimate the Drag Force on a Hand in Accelerated Flow

Problem: Let's say that from multiview synchronized videotapes, it is known that the velocity of Swimmer A's hand at the beginning of the freestyle insweep is 1.5 m/sec and the velocity at the end of the insweep is 3.5 m/sec. The videos show that this motion is accomplished in .30 seconds, and that the swimmer's hand is turned normal to the direction of motion (the angle of attack could have been chosen to be any angle, as long as the corresponding drag coefficient and projected area are consistent). The frontal area of the swimmer's hand is .018 m^2. Determine the average drag force on the hand during this .30 second insweep, and compare it with the quasi-steady drag force.

Solution: The hand drag force under accelerated flow will be calculated as:

$$\text{Ave Hand Acc. Drag} = \text{Ave Hand Q-Steady Drag} \times \frac{\text{Ave Disk Accelerated Drag}}{\text{Ave Disk Q-Steady Drag}}$$

Drag coefficients for a typical hand in steady flow have been determined by Schleihauf (18) and other authors for various angles of attack. If Schleihauf's results are used, a hand at an angle of attack of 90 degrees (normal to flow) has a drag coefficient of 1.35. For steady flow, the drag force may be calculated from Equation (1):

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}$$

Assume that the acceleration is constant between the start and end points of the insweep. Use the equation above to calculate the quasi-steady drag force at velocities of 1.5 m/sec, 3.5 m/sec, and two intermediate velocities of 2.166 m/sec and 2.833 m/sec. The calculated values are 27.25, 56.85, 97.22, and 148.35 Newtons. The time-averaged quasi-steady drag force of the hand during the .3 second sweep is calculated using these values to be 80.6 Newtons.

For the quasi-steady drag force on a disk of the same area (diameter = .1514 m, thickness = .01514m), and using the same equation at the same velocities with the drag coefficient of 1.17, the time-averaged force during the 0.3 second sweep is calculated to be 69.85 Newtons.

To determine the time-averaged disk accelerated drag force, first calculate the acceleration and average velocity during the sweep. The acceleration is (3.5-1.5)/.3 = 6.67 m/sec2. The average velocity is (1.5+3.5)/2 = 2.5 m/sec. Calculate the acceleration number aL/V^2 to be 0.16 and the parameter $\rho\forall a$ to be 1.81. Now use Figure 17 with these values to calculate the time-averaged accelerated disk drag force to be 86.88 Newtons.

Therefore, the Ave. Hand Accelerated Drag is:

$$80.6 \times \frac{86.88}{69.85} = 100.25 \text{ Newtons}$$

This is an 24% increase above the quasi-steady value of 80.6 Newtons.

Ms. Schloder is presently at the Department of Kinesiology and Coaching Sciences, University of Calgary.

Address for correspondence: Barry Bixler, M/S 93-32/301 120, Allied Signal Aerospace, P.O. Box 52181, Phoenix, Arizona 85072-2181 Phone: (602) 231-5989, Fax (602) 231-3018.

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Appendix

Another CFD Definition

Unsteady, three-dimensional (3D), compressible viscous flow is governed by the following equations:

The Continuity Equation (Conservation of Mass)
The Momentum Equations (Newton's Second Law: F =ma)
The Energy Equation (Conservation of Energy)

As a group, these equations are known to fluid dynamicists as the Navier-Stokes equations. They are a coupled system of nonlinear partial differential equations which to date have no known general closed-form solution.

CFD is a methodology that replaces the complex Navier-Stokes equations with discretized algebraic equations which can be easily solved by repetitive calculations on a computer. These algebraic equations associated with a CFD model are solved iteratively until a solution is obtained which satisfies the equations. Rather than obtaining a continuous closed form solution as in a theoretical analysis, CFD obtains fluid flow values (pressure, velocity, temp, etc.) at discrete points in time and space, as is done with experimental analyses. The details of this solution process are given below.

CFD Solution Steps

The algebraic equations associated with a CFD model are solved iteratively until a solution is obtained which satisfies the equations. Each iteration consists of the steps which were shown in Figure 1. These steps are described in more detail below:

CFD Solution Steps

1. The velocity field is updated after the momentum equations are each solved using current values for pressure.
2. The continuity equation and the linearized momentum equations are used to develop a pressure correction equation which is solved to obtain revised pressures and velocities.
3. The turbulence model equations are solved with the updated velocities.
4. Auxiliary equations, such as additional turbulence quantities, are solved using the values for the updated variables.
5. All fluid properties are updated.
6. The equations are checked for convergence. If convergence has occurred, the analysis is done. If not, steps 1-5 are repeated again.

How to Set Up a CFD Analysis

The basic steps in setting up a CFD analysis using one of the commercially available CFD codes are:

1. Establish the goals of the CFD analysis. Determine what results are required, and how accurate they have to be. CFD is an approximate numerical technique, and accuracy costs computer time and money.

2. Determine the geometry of the flow volume that is to be analyzed. Determine what its shape should be. Determine whether it should be modeled in two or three dimensions. Often it is best to start with a two-dimensional model before proceeding with a three-dimensional model.

3. Determine the fluid flow characteristics within the area of interest. Is the flow steady or unsteady? It is compressible or incompressible? Will there be significant separation of the boundary layer from the objects within or surrounding the flow? If the boundary layer separates, is it likely to reattach farther downstream?

4. Choose a CFD computer program and a solution method which best handles the physics of the problem. There are specialized CFD programs which are written for specific applications such as compressible hypersonic flow or two-phase flow, and there are general purpose codes which purport to handle almost any type of flow situation. No one code is the best for all situations, and which code is used is a matter of knowledge, experience, personal taste, availability, and cost. Most of the general purpose codes available to the public can handle the following variety of complex flow situations:

Steady state or transient unsteady flow
Compressible or incompressible flow
Attached or separated boundary layer
Laminar or turbulent flow
Coupled thermal analysis/fluid flow

5. Discretize the volume of fluid to be analyzed into a two-dimensional (2D) or three-dimensional (3D) "mesh" composed of small volume elements connected by grid points. Proper mesh alignment and refinement are critical in

performing an accurate CFD analysis. Mesh construction is done within the CFD code or by third-party software.

6. Specify the flow conditions along the boundary of the mesh. The flow conditions along the edges of the mesh are appropriately called "boundary conditions." Typical items for boundary conditions are pressure and velocity. Care must be taken not to overspecify the conditions along the boundary. Often some boundary conditions are unknown, and the program must calculate them.

7. Specify the fluid properties (viscosity, density, etc.)

9. Run the CFD code to calculate the solution.

10. Examine the results. Compare with analytical or experimental results if available.

11. Consider modifying the CFD model to achieve better results, and rerun it.

The FLUENT CFD Program

All CFD analyses in this study were performed with FLUENT, a commercial and widely available computer program for modeling fluid flow, heat transfer, and chemical reactions. In FLUENT, the governing fluid equations are solved using a finite volume technique, where the governing equations are integrated over each control volume. A segregated, pressure based algorithm is used that is good for incompressible or mildly compressible flows with turbulence or other complicating features. FLUENT handles interpolation with a first-order power law scheme or with high order upwind schemes, and uses a nonstaggered system for storage of discrete velocities and pressures.

FLUENT Turbulence Models

Three turbulence models are available in FLUENT, and all three were used in the solution process. The most accurate drag force calculations were achieved by first solving a problem with the standard k-ε turbulence model, switching to the renormalization group (RNG) turbulence model after k-epsilon convergence, and finally switching to the Reynolds turbulence model after RNG convergence. The turbulence intensity in all the analyses was 10%, and the characteristic length of the turbulence was 1 meter. The constants used in each of the turbulence models are given below:

Standard k-ε Model:

CMU, a constant used to compute the turbulent viscosity was 0.09

C1 and C2, constants used in the transport equations for ε, were 1.44 and 1.92, respectively.

E Prandtl, the effective Prandtl number for transport of turbulent kinetic energy, defines the ratio of the momentum diffusivity to the diffusivity of turbulent kinetic energy via turbulent transport. Its value was 1.0.

D Prandtl, the effective Prandtl number for transport of the turbulent dissipation rate, defines the ratio of the momentum diffusivity to the diffusivity of turbulence dissipation via turbulent transport. Its value was 1.3.

Renormalization Group (RNG) Model:

Alpha 0, which affects the prediction of transition, was 1.0

Viscosity Threshold Factor, which controls the differential function shape, was 1.0.

Reynolds Stress Model (RSM):

C1 Pressure Strain, empirical constant-default of 1.8 was used.

C2 Pressure Strain, empirical constant-default of 0.6 was used.

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Use of swim-training profiles and performance data to enhance training effectiveness

IÑIGO MUJIKA, JEAN-CLAUDE CHATARD, THIERRY BUSSO,
ANDRÉ GEYSSANT, FRÉDÉRIC BARALE* AND LUCIEN LACOSTE*

Laboratoire de Physiologie - GIP Exercice
Université Jean Monnet, Faculté de Médecine, Saint-Étienne, France
**Toulouse Olympique Étudiant Club, Toulouse, France*

Abstract

The purpose of this study was to evaluate individual responses of highly trained national and international level swimmers (n = 18) to training during a competitive season, using training and performance data. The different swim-training variables were statistically related with performance changes throughout the season, and a mathematical model which relates training with performance and estimates the negative and positive influences of training was also used (Mujika et al., in press). Several significant correlations were observed between training variables and individual changes in performance. For most of the subjects, strength training in the water, individual medley swimming and training at the speed of the 4 mM blood lactate accumulation correlated negatively with performance in the short-run ($P < 0.05$). The fit between modeled and real performance was significant for 17 of the subjects (r^2 ranged between 0.45 and 0.85). The modeled recovery time, t_n, and the time to reach the peak performance during supercompensation, t_g, ranged between 6 and 27 days, and between 19 and 56 days, respectively. These results indicate that training and performance data can be used to evaluate individual responses to a swim-training program and to enhance training effectiveness.

INDEX TERMS: Swimming, blood lactic acid, training assessment, coaching

Introduction

Swimming coaches intend to improve and maximize the capacities of their swimmers, in order to optimize performance. Training programs must be continuously adjusted to stimulate individual adaptation processes. However, training is often prescribed on the basis of simplified parameters, such as the distance swum or the amount of hours of training, which do not permit to reflect the physiological stress produced by the different forms of training (Sharp, 1993). Furthermore, swimming performance is often the only criterion available for coaches to evaluate the swimmer's degree of adaptation.

Training and performance data can be a useful tool for estimating individual adaptation profiles. Based upon these data, Mujika et al. (1995) proposed a swimming specific method for quantifying the total training load, which integrates swimming distance, training intensity and dryland weight training. These authors studied the influence of training components, detraining and initial performance level on performance changes in a group of elite swimmers during a training season. This quantifying method has also been used to model the responses to training and taper in a group of elite swimmers (Mujika et al., in press). According to this model, performance can be linked to the training stimulus by means of a negative function and a positive function, representing respectively the negative and positive influences of training on performance (Busso et al., 1992; Mujika et al., in press). However, the practical implications of those studies for the training regimen of the individual swimmer have not been developped.

It was the purpose of this study to propose a method of individually evaluating the responses to the different swim-training components, which only requires a precise quantification of the training content, regular assessments of the swimmer's performance level and simple statistical analyses. Moreover, the specific outcomes of the above mentioned study on mathematical modeling (Mujika et al., in press) to enhance training effectiveness will be analyzed.

Methods

Subjects

Eight women and ten men, national and international level swimmers, were the subjects of this study. Subjects gave their informed consent to participate in the study and did not suffer any experimental manipulation. They followed the training program prescribed by the team coaches. Swimmers had a mean background in competitive swimming of twelve years. Subjects' physical characteristics are presented in Table 1.

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Table 1. Subject characteristics. Means ± SD.

	Women	Men
Age (yr)	19.0 ± 1.6	21.4 ± 3.2
Height (cm)	171.5 ± 3.6	185.0 ± 5.3
Weight (kg)	58.3 ± 6.4	74.9 ± 9.6
Competition (yr)	10.4 ± 3.2	13.2 ± 4.3

Training

During an entire season, individual daily training logs of up to nineteen training variables were kept by the coaches. These variables included:

Training intensity. During a progressive test performed in the early season and consisting of 200-m swims at a progressively increased velocity until exhaustion, blood lactate concentrations were determined 1 min after each swim from fingertip blood samples. Swim training was divided into five intensity levels according to the individual results in the test. Intensities I, II and III were associated with swimming speeds inferior (≈ 2 mM), equal (≈ 4 mM) and slightly above (≈ 6 mM) the onset of blood lactate accumulation, respectively. High-intensity swimming eliciting blood lactate levels of ≈ 10 mM was defined as intensity IV, and sprint swimming as intensity V. All workouts were individually timed and each exercise categorized according to these intensity levels. Blood lactate tests were repeated during the season, and training intensity adjusted as the swimmer's lactate response was modified with training (Mujika et al., 1995; Mujika et al., in press).

Training volume. The training volume was quantified as the total distance swum by the subjects, in km.

Training frequency. Since swimmers were supposed to train twice a day, training frequency was determined by the number of half-days of rest.

Dryland training. Dryland weight training was quantified in min.

Other training variables. Other daily quantified training variables included: the distance swum in a 25 m or a 50 m pool; the distance of normal swimming, arm pulling alone or kicking alone; the distance covered swimming front crawl, medley or individual speciality; specific strength training by swimming against an increased resistance to advance; training to develop stroke frequency or distance per stroke.

Stress index scale

A blood lactate related stress index scale was established in an attempt to reflect the physiological stress produced by the exercises performed at the different intensity levels. The mean blood lactate values measured during swimming at intensities I, II, III and IV were 2, 4, 6 and 10 mM, respectively. A value of 16 was estimated for intensity V. These five values were then divided by two in order to make them more easily manageable. The final multiplying factors for the five intensity levels were therefore 1, 2, 3, 5 and 8, respectively (Mujika et al., 1995; Mujika et al., in press).

Training load

The total training load represents the total physiological stress produced by the different work-out sessions. In order to estimate the value of the total training load, measured in arbitrary training units, the number of km performed at each intensity level was multiplied by its corresponding multiplying factor. Furthermore, it was considered that 1 hour of dryland weight training was equivalent to 2 km in the water. An average weight training session was composed of 50 % warm-up and stretching exercises (close to intensity I), 25 % of submaximal strength exercises (close to intensity IV) and 25 % of maximal strength exercises (close to intensity V). Thus, 1 hour of dryland weight training represented 1 km of intensity I, 0.5 km of intensity IV and 0.5 km of intensity V (1 1 + 5 0.5 + 8 0.5 = 7.5). The total training load was then computed as follows :

Training load = 1 kmI + 2 kmII + 3 kmIII + 5 kmIV + 8 kmV + 7.5 H

where H is the number of weight training hours (Mujika et al., in press).

Performance

Subjects performed their competition speciality 18 ± 3 times during the season studied. The level of performance was expressed as the percentage of variation from the initial performance of the season.

Model formulation

The model considers the athlete as a system reacting with an output (performance) to a systems input (training). A transfer function, composed of two antagonistic first order filters representing a fatiguing impulse and a fitness impulse describes the systems behavior. These filters are calculated from the training impulse (Banister et al., 1975). In the study by Mujika at al. (in press), the model performance determined from the difference between the positive and negative functions at day n, $\hat{p}_n$, was calculated from the successive training loads from the first day of the study to the day of performance (w_i, with i varying from 1 to n-1):

$$\hat{p}_n = p^* + k_1 \sum_{i=1}^{n-1} w_i\, e^{-(n-i)/\tau_1} - k_2 \sum_{i=1}^{n-1} w_i\, e^{-(n-i)/\tau_2}$$

Modeled performances were defined with a positive and a negative multiplying factors, k_1 and k_2, a positive and a negative decay time constants, τ_1 and τ_2, and an additive term p^*, corresponding to an initial level of performance. Decay time constants are expressed in days, and other model parameters are expressed in arbitrary units depending on the units used in the quantification of the training load and performance. Model parameters are determined by minimizing the residual sum of squares of the fit between modeled performance and a real performance measured serially throughout the follow-up period.

Fitz-Clarke et al. (1991) defined as t_n the critical time period before competition within which training has a negative effect on performance. t_n, measured in days, is estimated by:

$$t_n = \frac{\tau_1 \tau_2}{\tau_1 - \tau_2} \ln \frac{k_2}{k_1}$$

t_g has been defined as the time before competition about which training contributes maximally to performance on the day of competition (Fitz-Clarke et al., 1991). t_g, measured in days, is computed as:

$$t_g = \frac{\tau_1 \tau_2}{\tau_1 - \tau_2} \ln \frac{k_2 \tau_1}{k_1 \tau_2}$$

Fatigue and fitness indicators have been computed from the combined effects of both model functions on performance (Busso et al., 1994 ; Busso et al., 1992). The influence of a training stimulus imposed at day i on performance at day n was calculated by the following equation:

$$I(i/n) = k_1 w_i e^{-(n-i)/\tau_1} - k_2 w_i e^{-(n-i)/\tau_2}$$

A negative value of I(i/n) indicated a negative influence of training on performance, while a positive value indicates a positive influence. The profile of the negative influence over the entire 44 wk long training season was determined by calculating the sum of this negative influence, NI_n, as follows:

$$NI_n = \sum_{i=1}^{n-1} |I(i/n)| \quad , \text{when } I(i/n) < 0$$

Since the estimated performance at day n, $\hat{p}_n$, is equal to the difference between the positive and the negative influence of training, the sum of the positive influence, PI_n, was computed as:

$$PI_n = \hat{p}_n + NI_n$$

NI is the negative contribution to performance of training performed until t_n days before competition. PI, on the other hand, is the positive contribution to performance of training performed before t_n days preceding competition. Thus, the indicators of fatigue and fitness used in the study by Mujika et al. (in press) were respectively NI and PI, expressed in arbitrary units, the dimensions of which were the same as those used for performance.

Statistical analysis

As no gender difference in training variables, performance changes and model variables was observed, the entire population was taken as a whole for all group statistical analyses. Individual correlations between the training variables and variation in performance were calculated from linear regression in two different ways : using the total values of the training variables of the week preceding each competition, and using the mean values of the weeks separating two competitions. Stepwise regressions were also calculated between swimming performance and the different training variables. Only the variables that added significantly to the prediction were included in the final regression equation. The statistical significance of the fit between actual performance and modeled performance was tested by an analysis of variance on the residual sum of squares. The level of significance of the fit was estimated from the F - test. The 0.05 level of significance was adopted.

Results

Relationships between training variables and performance

Table 2 shows the significant coefficients of correlation observed for each subject between the variation in performance throughout the season and the training variables, calculated with the values of the training performed during the week preceding each competition. Positive correlations indicated a decline in performance and vice versa. The distance swum at the speed of the 4 mM blood lactate accumulation (Intensity II), medley swimming (Medley) and the specific strength training in the water (Strength) were the variables correlated with a loss in performance for a higher number of swimmers. They were significant for 13 or 14 of the subjects. Similar results to those reported in Table 2 were obtained when the correlations between training and performance were computed with the mean training values of the weeks separating two competitions. Examples of training variables resulting in a decline in performance and an improved performance can be seen in Figure 1 A and B, respectively.

These results were confirmed when, instead of individually, the same procedure was followed for the entire group of swimmers. Indeed, when considering the week preceding each competition, the correlations between the variation in performance and Strength, Medley and Intensity II were statistically significant ($P < 0.001$) : $r = 0.49$, 0.47 and 0. 45, respectively, and $r = 0.45$, 0.44 and 0.37 when calculations were made with the mean amount of training of the weeks between two competitions.

Stroke rate was the only variable correlated with gains in performance. This correlation, however, reached statistical significance for only three of the subjects.

Table 2. Coefficients of correlation between the variations in performance throughout the season and the quantified training variables. Only significant correlations are shown.

	Subject																	
Variable	1 (W)	2 (M)	3 (M)	4 (M)	5 (W)	6 (W)	7 (W)	8 (M)	9 (W)	10 (W)	11 (W)	12 (W)	13 (M)	14 (M)	15 (M)	16 (M)	17 (M)	18 (M)
Frequency				0.64		0.53				0.54	0.61	0.58				0.63		
Volume	0.76	0.50	0.68				0.61	0.77	0.82				0.66		0.59			
Intensity I	0.69		0.68					0.69	0.80									
Intensity II	0.64	0.61	0.45	0.50			0.71	0.68	0.77		0.80	0.53	0.80		0.59	0.71	0.61	0.54
Intensity III								0.58	0.58							0.64		
Intensity IV																		
Intensity V	0.59							0.59					0.83					0.61
50 m Pool			0.49						0.56									
25 m Pool	0.67			0.60	0.56			0.68	0.66				0.65					
Normal Swim	0.69	0.51	0.63				0.61	0.73	0.79				0.71		0.60	0.61		
Arm Pulling	0.66		0.73				0.59	0.74	0.82									
Kicking	0.67		0.48	0.49				0.75	0.74				0.63		0.61	0.75	0.61	
Crawl	0.68	0.51	0.55				0.68	0.66	0.86						0.50			
Medley	0.87	0.52	0.67	0.64			0.58	0.79	0.78		0.73	0.52	0.77		0.58	0.75		0.65
Speciality	0.52		0.59					0.71	0.67									
Strength	0.76	0.53		0.46			0.53	0.83	0.70		0.77	0.74		0.81	0.70	0.62	0.51	0.70
Stroke Rate										-0.66	-0.51			-0.66				
Distance/Stroke	0.49							0.54	0.55				0.73			0.63	0.49	0.59
Weight Lifting	0.57	0.54					0.71		0.74						0.59		0.56	

W: Woman; M: man.

Application of the model

Model results from the study by Mujika et al. (in press) are presented with permission of Medicine and Science in Sports and Exercise. Figures 2 and 3 show the results of the application of the model for two of the subjects, with the weekly training load in graphic C, the negative and positive influence profiles in graphic B and the fit between actual performance and modeled performance in graphic A. The positive and negative time constants of decay, τ_1 and τ_2, ranged between 30 and 70 days (mean ± SD 41,4 ± 12,5) and between 0 and 20 days (12,4 ± 6,9), respectively. The individual recovery time, t_n, and the time to reach the peak performance during the supercompensation period, t_g, ranged between 6 and 27 days (12,2 ± 5,7), and between 19 and 56 days (31,5 ± 11,6), respectively. One of the subjects, however, presented values of 0 days for these two variables.

Positive correlations were observed between the number of variables significantly correlated with performance for each subject and the values of t_n and t_g. However, only the latter reached the level of statistical significance (r = 0.42, P = 0.09 and r = 0.53, P < 0.05, respectively).

Table 3 shows the values of the coefficients of determination (r^2) calculated for each swimmer with the stepwise regression method and with the performance fit of the model. These values ranged between 0.28 and 0.78 for the stepwise regression, and between 0.45 and 0.85 for the performance fit.

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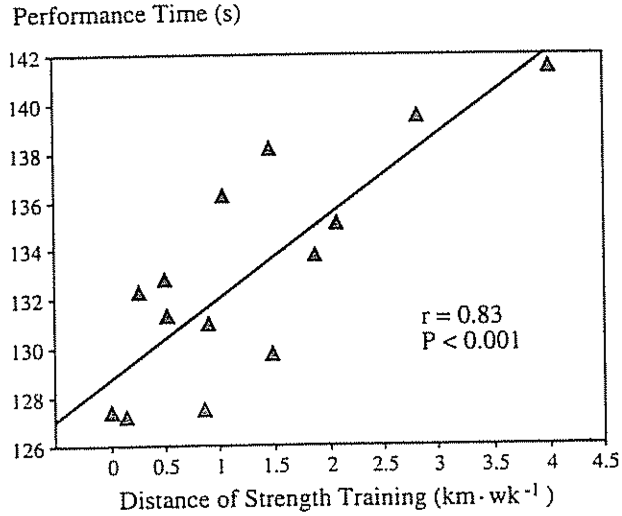

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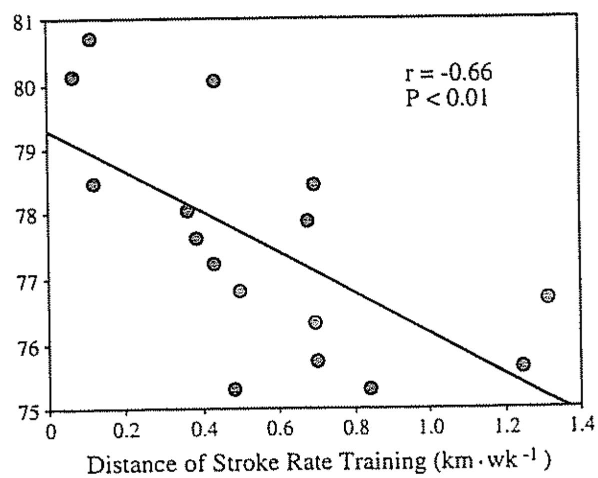
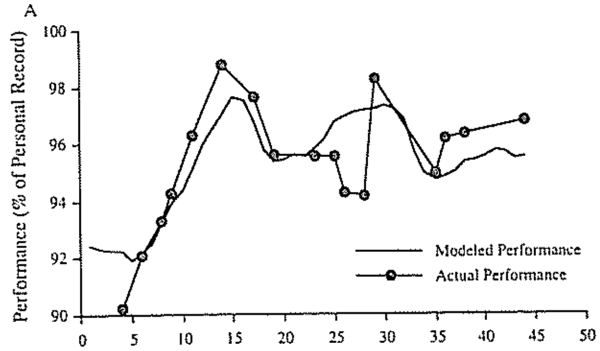


Figure 1

A



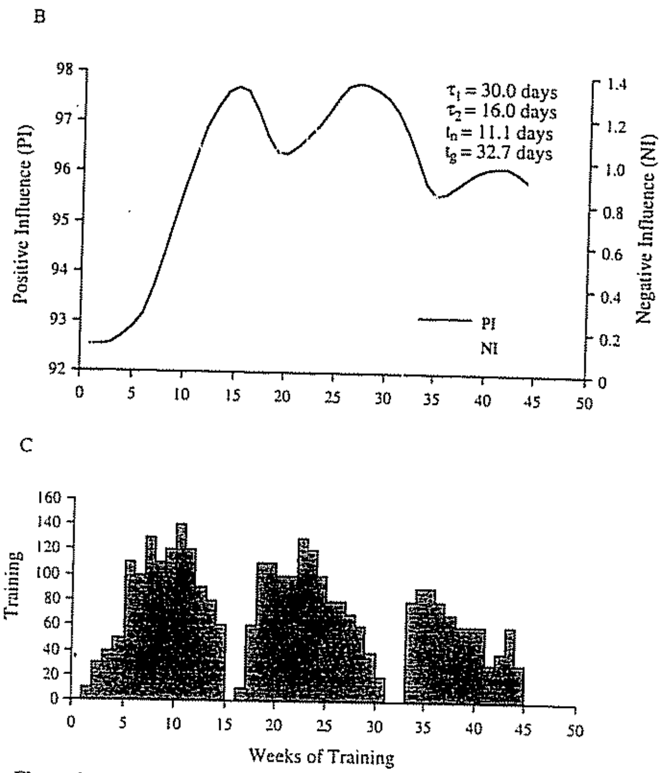


Figure 2

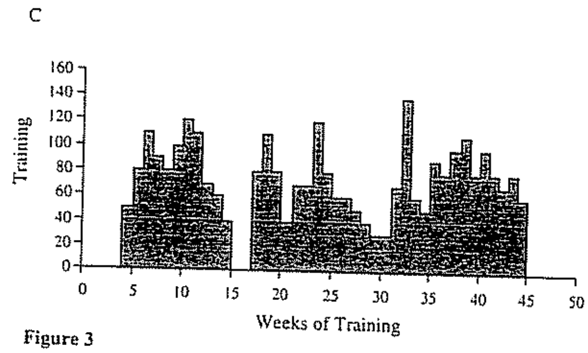


Figure 3

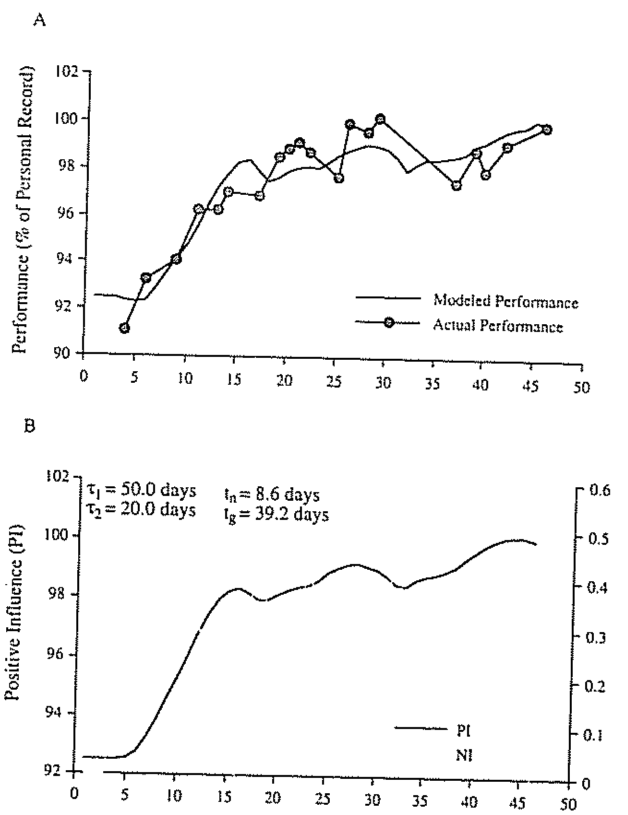


Figure legends

Figure 1. A: relationship between specific strength training in the water and performance time (subject 8). B: relationship between training to improve the stroke rate and performance time (subject 10).

Figure 2. Application of the model for subject 15. A: performance fit. B: negative and positive influence profiles. C: Training load. τ_1 and τ_2: time constants of decay of the positive and negative influences of training on performance, respectively. t_n: time period before competition within which training has a negative effect on performance. t_g: time before competition about which training contributes maximally to performance on the day of competition. All the variables are expressed in the type of unit used in the quantification of performance. Figure drawn with permission from the results obtained in the study of Mujika et al., Medicine and Science in Sports and Exercise, in press.

Figure 3. Application of the model for subject 1. A: performance fit. B: negative and positive influence profiles. C: Training load. τ_1 and τ_2: time constants of decay of the positive and negative influences of training on performance, respectively. t_n: time period before competition within which training has a negative effect on performance. t_g: time before competition about which training contributes maximally to performance on the day of competition. All the variables are expressed in the type of unit used in the quantification of performance. Figure drawn with permission from the results obtained in the study of Mujika et al., Medicine and Science in Sports and Exercise, in press.

Table 3. Individual coefficient of determination values calculated from the stepwise regression (r^2 step) and from the performance fit (r^2 model).

Subject	r^2 step	r^2 model
1	0.76	0.85
2	0.37	0.72
3	0.54	0.63
4	0.53	0.45
5	0.31	0.65
6	0.28	0.55
7	0.51	0.53
8	0.78	0.67
9	0.74	0.49
10	0.44	0.58
11	0.72	0.63
12	0.66	0.59
13	0.79	0.76
14	0.66	0.85
15	0.49	0.57
16	0.57	0.80
17	0.37	0.69
18	0.48	0.66
Mean	0.56	0.65
SD	0.16	0.12

Discussion and applications

Coaches must often evaluate the adaptation level of the swimmers from the training content and performance data, since these are sometimes the only parameters available for them. These simple and easily attainable parameters, nevertheless, can lead to interesting and useful results and conclusions. Indeed, previous studies on competitive swimming have used training and performance data in order to determine the influence of training intensity, volume and frequency on performance changes during a swim-training season (Costill et al., 1991; Mujika et al., 1995). Moreover, the elite swimmers' performance capacity has been shown to be influenced by the effects of detraining during the off-season and by the initial performance level (Mujika et al., 1995). Swimmers' responses to training and taper have also been studied and modeled from training and performance data (Costill et al., 1985; Johns et al., 1992; Mujika et al., in press).

Significant correlations were found for each subject between the variations in performance and some of the remaining training variables. As can be seen in Table 2, for some of the swimmers studied, several training variables correlated with a decline in swimming performance (e. g. subjects 1, 8, 9), while for some other swimmers these relationships were very scant (e. g. subjects 5, 6, 10, 14). This observation could indicate that the former swimmers had a higher sensitiveness to the training stimulus than the latter, since most training variables initially affected them in a quite negative way. Two observations seem to confirm this interpretation. First, the longer recovery and supercompensation times of the subjects with a higher number of correlations, as shown by the relationship between t_n, t_g and the number of individual correlations. Second, the fact that a low training frequency (or a high amount of half days of rest) had a negative effect on performance in some of the swimmers with a low number of significant correlations. The analysis of the relationships between the training variables and the variations in performance for each swimmer could thus be a helpful tool for coaches and swimmers, in order to establish individualized training programs based on individual adaptation profiles, specially during periods of taper.

The main advantage of the mathematical model from a practical point of view, is that it evaluates individual adaptation processes by means of negative and positive influence profiles, which are estimated by relating training, quantified by integrating water and dryland training volume and intensity, with performance. Indeed, several studies have associated the modeled fatigue and fitness profiles with the variations of biological parameters in response to different athletic training situations (Banister and Hamilton, 1985; Busso et al., 1990; Busso et al., 1992). The application of the model could thus help coaches to better evaluate the individual responses to training. The two subjects presented in Figures 2 and 3, for example, showed different adaptation profiles. The positive influence level of the subject in Figure 2 (subject 15) reached its highest point by week 15, and then went down and up at different moments of the season, ending at a relative low level. The subject in Figure 3 (subject 1), on the other hand, had a much more progressive adaptation profile. The positive influence increased fast during the first 16 weeks, and it then continued increasing at a slower rate, reaching its maximum level at the end of the training season. The negative influence followed a very similar pattern in both subjects, reaching its highest levels during hard training periods and lowest levels during the reduced training periods preceding the main competitions. The subject in Figure 3, however, had lower levels of negative influence than the subject in Figure 2, as shown by the scales in the graphics.

The available body of data for subject 15 indicated a fast disappearance of the positive influence of training, while the time constant of decay for the negative influence of training, the recovery time and the necessary time to reach peak performance were close to the mean group values. These results suggest that taper should not be too long for this swimmer, in order to avoid a quick detraining effect due to the reduction in training. Moreover, specific strength training (swimming against an increased resistance to advance) and kicking seemed to have a negative effect on his performance capacity in the short run, which suggests that these training modes should be reduced or avoided before the major competitions. Results for subject 1 indicated a general state of fatigue (a slow decay of the negative influence of training, a long time necessary to reach peak performance, and most of the quantified training variables producing a negative effect on performance). This swimmer would need a long period of taper to enhance recovery processes and optimize performance. In contrast with subject 15, a long taper would not negatively affect his fitness level, since he presents a slow decay of the positive influence of training.

In the present study, the values of the training variables during the week preceding each competition showed many correlations with declines in performance. This could be explained by the initial fatiguing effects of the training sessions. In the present study, three variables appeared as the most fatiguing in the short term : strength training in the water, individual medley swimming and training at the speed of the 4 mM blood lactate accumulation. Since these aspects of training seem to have a negative short term effect on performance, it could be suggested that they should be avoided during the periods of taper immediately preceding important competitions. This kind of analysis could thus be used to evaluate the short term effects of the different training variables on performance. Their possible contribution to the long term physiological adaptations, however, cannot be assessed from the results of the present study.

The different training variables included in the final regression equation of each swimmer accounted for 28 to 78 % of the variation in performance, as shown by the values of the coefficients of determination presented in Table 3. The r^2 values of the fit between actual performance and modeled performance ranged between 0.45 and 0.85 (Mujika et al., in press). This suggests that, even though an important part of the variations in performance experienced by the swimmers of the present study remained unexplained, these two methods are valuable instruments in order to describe the relationship between training and performance in competitive swimming.

In conclusion, the present study shows that individual adaptation profiles can be estimated from swimming training and performance data. Studying individual relationships between training content and performance by means of simple and stepwise regression analysis, along with the individual negative and positive influence profiles derived from the mathematical model of the effects of training on performance (Mujika et al, in press), can help coaches in the task of evaluating the swimmer's responses to training. The evaluation methods proposed could be useful tools in order to adapt and improve training programs, by individualizing training according to each swimmer's specific responses and reactions.

Address for correspondence: Iñigo Mujika, Departmento de Alto Rendimiento, Instituto Vasco de Educacion Fisica, Soin Hezkuntzaka Euskal Erakundea, Carretera Lasarte s/n, 01007 Vitoria-Gasteiz, Basque Country, Spain, Phone: (34) 45 13 33 63, Fax: (34) 45 13 34 46.

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Recovery from maximal swimming at the predicted initial onset of blood lactate accumulation.

MELANIE T. RICHARDSON, DEAN ZOERINK, KARL F. RINEHARDT, MICHELLE CORDILL, NANCY BOUCHIER, AND CLIFF LATHAM

Southern Connecticut State University
New Haven, Connecticut 06515

Abstract

Fifteen male high school swimmers were subjects in a study to; 1) produce lactate profiles that accurately depict the initial onset of blood lactate accumulation (IOBLA), and 2) investigate the efficacy of the IOBLA workload for removing blood lactate during swimming recovery. To determine the accuracy of the lactate profiles, heart rates and blood lactates were compared from the IOBLA of the lactate profiles to those respective values observed following 30 minutes of recovery swimming at the IOBLA intensity. Individual lactate profiles were produced from six 4 minute swims performed at 33 to 81% of maximal workload. No significant differences existed for mean heart rate (131±10 vs 136±17 bpm) or blood lactate (1.6±0.3 vs 1.6±0.4 mmol·l^{-1}), between the IOBLA of the lactate profile and at 30 minutes of recovery, p≥0.05. Recovery results showed that blood lactate decreased 8.5 mmol·l^{-1} to initial IOBLA values; an overall rate of 3.7%·min^{-1} during 30 minutes of recovery. Half the blood lactate was removed in ~8.0 minutes. A rapid linear decline in lactate occurred from 0-18 minutes in which 76% of maximal lactate was removed. Results indicate lactate profiles developed using the present protocol represent similar workload-IOBLA relationships as observed during prolonged recovery swimming, and that the IOBLA workload is a specific workload for removing blood lactate optimally after maximal swimming exercise.

INDEX TERMS - IOBLA, baseline, lactate profile, steady state, $t^{1/2}$, lactic acid, competitive swimming, lactic threshold

Introduction

High school, collegiate, and international caliber swimmers are often required to perform competition and training swims of 50 to 400 meters (m) repeatedly with short rest periods separating the swims. Energy (ATP) production during such high intensity exercise is beyond the sole capability of the aerobic system and, therefore, significant ATP production is derived from anaerobic glycolysis; with the amount dependent upon the distance and velocity at which the swims are performed (1). As a result, lactic acid a by-product of anaerobic glycolysis and a substance associated with fatigue, accumulates in muscle and blood (8,20). Exercise recovery has been shown to remove lactate more rapidly than rest recovery and hasten the athlete's return to baseline conditions. Research findings suggest that during exercise recovery muscle itself is the dominant organ responsible for metabolizing (clearing) lactate (2).

Results by Stamford et al. suggest the optimal recovery intensity is specific to each individual, and is one that allows muscle to function at the highest aerobic workload without causing a rise in blood lactate concentration above baseline or initial onset of blood lactate accumulation (IOBLA) levels. The IOBLA intensity can be determined from a lactate profile, which is the graphed relationship between swimming workloads and corresponding blood lactate concentrations. However, the accuracy of the lactate profile for depicting workload-lactate relationships has not been substantiated, and in fact several studies have demonstrated that workload-lactate relationships depicted by lactate profiles are not maintained during prolonged steady state swimming (6,14,-22). Furthermore, a review of the literature indicates that the effectiveness of the IOBLA intensity for removing blood lactate during swimming recovery has not been investigated.

Therefore, the purpose of this investigation was to: 1) determine whether lactate profiles, produced using a discontinuous swimming protocol, accurately depict the workload-IOBLA relationship, and 2) investigate the efficacy of the IOBLA workload for removing blood lactate during swimming recovery.

Materials and Methods

Subjects

Fifteen male high school swimmers 14-18 years of age who were engaged in training and were approaching the taper phase of the swimming season volunteered as subjects for this investigation. The investigation was approved by the Institutional Research Board of the University, and potential subjects were informed verbally and in writing about the conduct of the study. Volunteers then signed an Informed Consent Form prior to data collection. All subjects under 18

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years of age were also required to have a parent or legal guardian read and sign the Informed Consent. Descriptive information of the subjects is shown in Table 1.

Table 1: Descriptive information of subjects. (n=15)

Subjects	Mean ± SD
Age (yr)	16.3 ± 1.0
Height (cm)	175.8 ± 6.0
Weight (kg)	71.5 ± 13.2
VO_{2max} (ml ·kg^{-1}·min^{-1})	62.1 ± 10.6
Swim Experience (yr)	4.7 ± 0.8
Daily Training Distance (m)	3152 ± 1028
Range of Daily Training (m)	2425 – 3880

Lactate Profile IOBLA Determination Test

On day one, subjects swam and kicked 400 yards (366 m) for warmup and rested for a minimum of 10 minutes. Subjects then performed six 4 minute tethered swims at resistances of 33, 40, 51, 62, 70, and 81% of their predetermined maximal tethered workload. (Maximal workload was determined previously using a continuous progressive tethered swimming protocol of between 8-12 minutes formulated by William Heusner at Michigan State University.) One minute of rest separated the swims during which time heart rates were measured using Polar Vantage XL monitors and 25*ul* of capillary blood for lactate determination was obtained from the fingertip and analyzed using a Yellow Springs Instrument Inc. (YSI) 2300 G/L analyzer.

Workload-lactate data were then graphed to develop individual lactate profiles. Each subject's IOBLA was selected as the workload where blood lactate began to rise above steady state baseline values of the initial swims. This lactate concentration was used rather than the more variable resting level which is influenced by anxiety. To locate the IOBLA workload, a line was drawn through the first 2 data points above baseline lactate, then extrapolated to baseline lactate and dropped vertically to the corresponding workload. This is depicted in Figure 1. Regression analysis of all data points above baseline lactate, established that the workload-lactate relationship was significantly linear, $p \leq 0.05$, which supports using this method for locating the IOBLA. The accuracy of the lactate profile to depict the IOBLA was determined by comparing heart rates and blood lactate concentrations from the IOBLA of individual lactate profiles to the respective values following 30 minutes of recovery performed at the depicted IOBLA intensity.

Blood Lactate Recovery Test

On day two, subjects performed an exhaustive, progressive load, tethered swim to determine maximal aerobic capacity (VO_{2max}), maximal blood lactate accumulation, and a blood lactate recovery curve. Initially, subjects swam against a

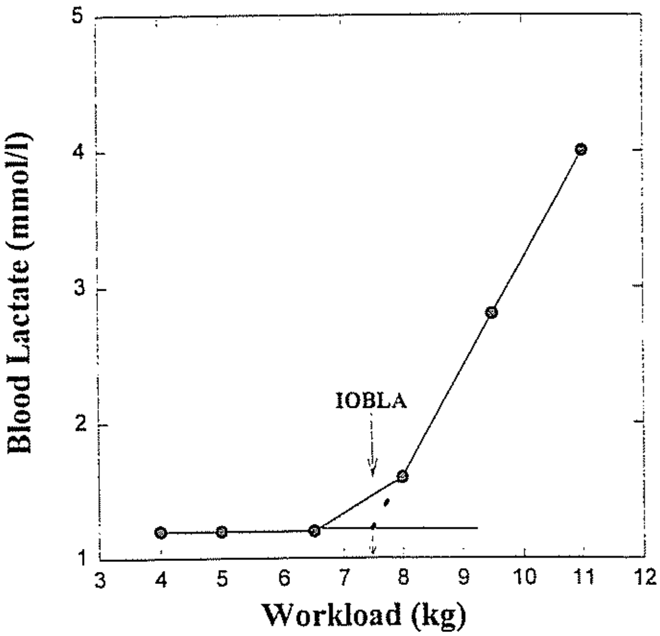

Figure 1. Workload-blood lactate relationship of an individual lactate profile. Dotted line represents extrapolation to baseline lactate. Vertical arrow drops to corresponding workload.

warmup resistance of 1.5-2.0 kg for 3 minutes, after which 2 kg was added to the apparatus for an additional one minute. Thereafter, 0.5 kg of weight was added to the apparatus every 30 seconds until the subjects reached exhaustion; at which time VO_{2max} and heart rates were measured. Exhaustion occurred when subjects were unable to hold a stationary position and were pulled backward by the load on the tether apparatus. Subjects then continued to rest quietly into 3 minutes of recovery. All athletes performed the swimming tests using the freestyle stroke while attached to a double-pulley tether apparatus.

Between 2:30 and 3:00 minutes of quiet rest, blood was obtained from the fingertip for analysis of maximal blood lactate concentration using the same procedures described above. Unpublished data from our laboratory using subjects of comparable aerobic capacity have shown that maximal blood lactate concentrations following maximal exercise occur between 2:00 and 4:00 minutes of quiet rest. At precisely 3:00 minutes, heart rates were recorded and subjects began a tethered recovery swim against a workload corresponding to their IOBLA. At minutes 6, 10, 14, 18, 22, 26, and 30 of swimming recovery, heart rates were measured and blood was obtained from the finger tip for lactate analysis. Heart rate and blood lactate data at each recovery time period were then computed in regression analyses.

Statistical Analyses

Linear and quadratic regression analyses were performed to determine relationships for workload-heart rate and workload-lactate from lactate profiles, and for time-heart rate and time-lactate during recovery. Paired t-tests were performed to detect significant differences between 1) heart rate at the lactate profile IOBLA and heart rate at 30 minutes of recovery, and 2) between blood lactate concentration at the lactate profile IOBLA and blood lactate concentration at 30 minutes of recovery.

Results

Mean±SD data for heart rate and blood lactate at each workload of the lactate profile test are shown in Table 2. Regression analyses revealed that the workload-heart rate relationship was significantly linear, whereas the workload-lactate relationship was both significantly linear and curvilinear, $p \leq 0.05$. When the mean±SD heart rate of 131±10 bpm and blood lactate of 1.6±0.3 $mmol \cdot l^{-1}$ from the lactate profile IOBLA was compared to respective values of 136±17 bpm and 1.6±0.4 observed at 30 minutes of recovery swimming, no significant differences existed, $p \geq 0.05$. Furthermore, a comparison of the mean IOBLA heart rate of 131±10 bpm and workload of 6.00±0.91 kg to the mean maximal heart rate of 185±11 bpm and workload of 12.72±1.29 kg from the exhaustive tethered swim, indicates that IOBLA occurred at 71% of maximal heart rate and 47% of the highest workload achieved.

Table 2: Mean ± SD for workload, heart rate, and blood lactate for each stage of the lactate profile swimming test. (n=15)

Stage	Workload (kg)	Heart Rate (bpm)	Blood Lactate (mmol/l)
1	4.15 ± 0.39	123 ± 11	1.6 ± 0.3
2	5.10 ± 0.60	128 ± 12	1.6 ± 0.3
3	6.48 ± 0.79	137 ± 13	2.1 ± 0.5
4	7.90 ± 1.01	150 ± 14	2.9 ± 0.8
5	9.28 ± 1.26	163 ± 14	4.4 ± 1.3
6	10.25 ± 1.80	169 ± 14	5.0 ± 1.4

Mean±SD data for heart rate and blood lactate during 30 minutes of recovery are graphed in Figure 2. Blood lactate concentrations decreased 8.5 $mmol \cdot l^{-1}$ from a maximum of 10.1 $mmol \cdot l^{-1}$ to IOBLA values of 1.6 $mmol \cdot l^{-1}$, an overall rate of 3.7%$\cdot min^{-1}$. Linear and curvilinear regression analyses of 30 minutes of recovery showed the time ($t^{1/2}$) to remove half of the blood lactate (4.3 $mmol \cdot l^{-1}$) was 8.1 and 7.8 minutes, respectively, which represents 0.5 $mmol \cdot l^{-1}$ or 6.3% of blood lactate removed per minute. Further analysis of the early portion of the swimming recovery curve (0-18 minutes) indicates a rapid linear decline in lactate concentration to 2.5 $mmol \cdot l^{-1}$ representing 76% of blood lactate removed during this time period.

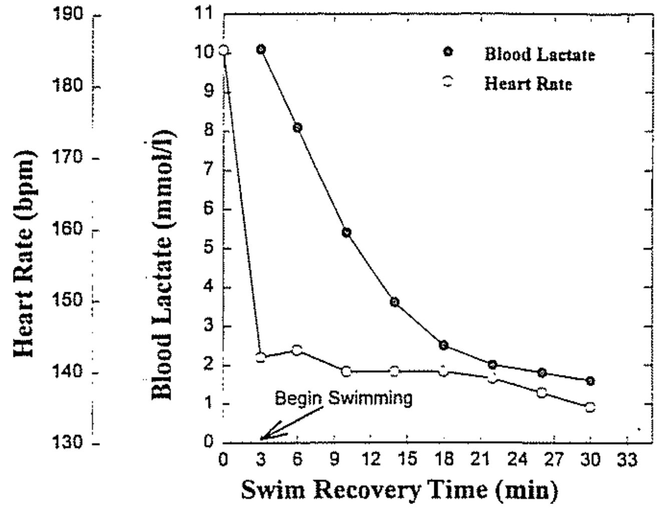

Figure 2. Mean data points for workload-heart rate, and workload-blood lactate during 3 minutes of rest and 27 minutes of recovery swimming at the IOBLA workload.

Discussion

Insignificant differences for heart rates and blood lactate concentrations between the lactate profile IOBLA and following 30 minutes of recovery at the IOBLA workload suggest the present methodology is accurate for producing lactate profiles and locating IOBLA workloads.

Review of previous data indicates that metabolic thresholds occur at rather precise workloads. Green et al. report "considerable inter-individual variability" in power outputs corresponding to the IOBLA during stationary cycling. Moreover, as little as a 5% deviation in workload from an individual's anaerobic threshold (OBLA) has been reported to cause premature fatigue during endurance performance (22). Data from the present study support the individuality of thresholds with standard deviations of ±15% and ±20%, respectively, for the mean IOBLA workload and blood lactate concentration of the lactate profiles.

Recognized swimming protocols by Mader et al., Madsen and Lohberg, and Olbrecht et al. for producing lactate profiles require that an athlete perform 2-5 swims for approximately 4 minutes, with each stage separated by 15-30 minutes of rest. These protocols, however, are inaccurate for predicting blood lactate levels during prolonged steady state swimming at intensities depicted by lactate profiles. In a study by Hein et al., lactate accumulation following steady state swimming differed significantly from the workload-lactate relationship exhibited by lactate profiles, even though the suggested protocol to develop the profiles was followed. Hein's subjects performed 5 swims of roughly 4 minutes duration separated by 30 minutes of active and inactive rest. The following day subjects performed a set of 14x183 m freestyle steady state swims with 10 seconds rest at a specified profile workload. Reported mean blood lactate concentration at the completion of the prolonged swimming set was significantly less (2.95 $mmol \cdot l^{-1}$) than that depicted by the lactate profile (4.07 $mmol \cdot l^{-1}$). Hein et al. concluded that the efficacy of the protocol for determining workload-lactate relationships during prolonged steady state swimming was unclear. Furthermore, in a study by Olbrecht et al., lactate concentrations following 30 and 60 minutes of continuous swimming and following repeat 50, 100, 200, and 400 m steady state freestyle swims differed significantly from those predicted from a two-point lactate profile (2x400 m) whose methodology included 20 minutes of rest between swims.

It is generally recognized that differences exist between the workload-lactate relationship of lactate profiles and steady state swimming because steady state lactate is not attained during profile protocols (22). Several methodological factors contribute to this situation. Duration of exercise stages are abbreviated and/or the incremental increase in intensity is excessive thus disallowing equilibration of lactate to occur between muscle and blood. In short, the transport dependent efflux of lactate has insufficient time to attain a steady state condition between muscle and blood lactate. Our exercise protocol differed from both Hein et al. and Olbrecht et al. in that the incremental difference between successive swims was minimal (10%) and we only allowed one minute of rest between the swims instead of the typical 15-30 minutes. We contend the rest period was of appropriate short duration to maintain an elevated metabolic rate thus keeping metabolic differences between consecutive workloads to a minimum. Consequently, swimmers were "properly warmed up" for the next swim and could truly reach a new steady state blood lactate level within the subsequent 4 minute period. Further support for this hypothesis is that during mild exercise, the lag time for lactate efflux from the muscle to the blood is approximately 90 to 120 seconds (16,24), and that steady state lactate across the muscle membrane is achieved more rapidly at milder compared to intense exercise workloads. (22). Since the IOBLA occurred at only 47% of the highest workload achieved in our subjects, it is understandable that steady state blood lactate was reached using our protocol.

The effect of elevated blood lactate on subsequent performance is equivocal, with some studies reporting an inhibition of subsequent performance (8,9) and others reporting that levels of blood lactate ranging from approximately 6 to 12 Mm had no significant effect on performance (23). Nonetheless, the clearance of blood lactate has been shown to be associated with recovery of muscular force (20).

The removal of blood lactate during recovery is affected by multiple factors including the efflux rate of lactate from muscle to blood (16), muscle capillary density (20), blood flow rate (4), and metabolic removal by various organs such as heart, liver, and muscle (2); with exercising muscle being the dominant organ responsible for removing 55-70% of total lactate via oxidative processes (2). During exercise recovery, an optimal efflux rate of lactate from muscle into blood is maintained; compared to rest recovery. Increased blood flow past the exercising muscle continually dilutes the blood lactate concentration immediately adjacent to the muscle membrane. In effect, the muscle lactate transporter is able to move lactate at an optimal rate from an area of high concentration (muscle) into an area of low concentration (blood) where it then is transported to the above mentioned organs for metabolic removal (22).

Conceptually, an optimal recovery workload should be one that allows muscle to function at the highest aerobic capacity without accumulating blood lactate. Highly significant relationships reported by Ivy et al. for muscle respiratory capacity and composition of slow twitch fiber to both absolute and relative lactate thresholds (IOBLA) support this concept. Accordingly, our results also support this concept when compared to other swimming studies. In the present study, the $t^{1/2}$ across 30 minutes of recovery was 7.8 to 8.1 minutes compared to 11.4, 11.9, and 11.9 minutes reported by Cazorla et al. for swimmers who performed three 20 minute recovery swims at 60, 71 and 75% of their 100 m maximal velocity. In an attempt to equate workloads to Cazorla's, our subjects' heart rates during the initial 20 minutes of recovery returned to 140 bpm, which compares closely to the mean heart rate of the 71% velocity swim in Cazorla's study (141 bpm). However, our subjects cleared blood lactate in approximately 3.4 minutes less or 30% more rapidly than Cazorla's subjects. Recovering at the IOBLA intensity also was effective compared to intensities used in a study by McMaster et al. in which six swimmers performed 15 minutes of recovery swimming at 55, 65, and 75% of their 200 m maximal velocity. Analyses of McMaster's data indicate the mean $t^{1/2}$ time of the three trials approximated 8.6 minutes in which 2.9 $mmol \cdot l^{-1}$ of blood lactate was removed compared to the present study's $t^{1/2}$ of approximately 8.0 minutes in which 4.3 $mmol \cdot l^{-1}$ was removed. Recovering at the IOBLA intensity cleared 33% more blood lactate in 7% less time than across a range of 55-75% of maximal swimming velocity. Therefore, similar to suggestions by Stamford et al. our data suggest the workload corresponding to the IOBLA is a specific recovery intensity for the swimming athlete, allowing the athlete to return rapidly to a competitive physiological condition. Although, recovery intensities slightly lower or higher than the IOBLA may be similarly effective and should be investigated.

Practical Application

The intent of this study was to accurately locate the IOBLA, and to determine the efficacy of the IOBLA for removing blood lactate during swimming recovery. The results indicate that a discontinuous protocol with short rest periods of one minute coupled with small incremental differences (10%) between successive intensities appears to be effective in producing a lactate profile from which the IOBLA intensity can be located. Moreover, the results of this study have shown that the athlete's specific IOBLA intensity removes blood lactate more rapidly than previously reported intensities.

The increased reliability, availability and simplicity of automated lactate analyzers permit coaches, athletes and exercise physiologists to easily monitor metabolic adaptations or "changes in training thresholds" during training seasons. Lactate profiles are used in diagnostic and prescriptive manners to enhance the quality of training, expedite recovery from intense exercise, and ultimately improve and predict competitive performance (6,11,12,13,17). Specifically, the IOBLA is strongly related to endurance performance (19), and is recommended as an intensity to recuperate from intense anaerobic training (1,11,18). Consequently, the United States Swimming Medicine Committee recommends practicing at the IOBLA as an integral component of routine seasonal training (21). Therefore, accurate location of this initial deflection point is important to coaches and athletes for proper training prescription.

The practicality of the IOBLA as a recovery intensity seems obvious. The results suggest this swimming intensity is very specific to the individual athlete and enables the athlete to quickly clear excess blood lactate and return to a more conducive pre-competitive condition. Furthermore, being a very mild intensity the exhausted athlete is physically and psychologically more willing to perform an exercise recovery. Practicality is also found in the design of the recovery. Although coaches encourage their swimmers to begin cooling down immediately following the completion of a competitive or timed training swim, athletes are interested in "catching their breath", inquiring about their performance time, and often desire feedback from their coaches before beginning a cool-down. The fact is that swimmers naturally delay beginning a cool-down and then stop periodically during the cool-down. The present recovery format included a three minute delay before beginning swimming recovery with subsequent one minute breaks after every three minutes of swimming recovery; similar to the natural pattern selected by swimmers. Given the rapid recovery at the IOBLA intensity it appears that cool-down does not need to be a regimented continuous swim as once thought and in fact can be a relaxing period for the exhausted athlete to communicate to his/her coach and teammates and still prepare for subsequent swims.

Ms. Richards is presently at the Army Physical Fitness Institute, U.S. Army War College, Carlisle, PA. Mr. Zoerink is presently at Western Illinois University, Leisure Studies, 400 Currens Hall, Macomb, IL. Ms. Cordill is presently at 1501 North 48th Street, Apt. #5, Omaha, NE. Ms. Bouchier is presently at McMaster University, Dept. of Kinesiology, Hamilton, Ontario, Canada. Mr. Latham is presently at 101 East Mission St., St. Marys, KS.

Address for correspondence: Karl F. Rinehardt, Ph.D., Southern Connecticut State University, Exercise Science Dept. 10-Pelz 3, New Haven, Connecticut 06515, Phone: (203) 392-6095.

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Fluid Loss in Swimmers

PETER REABURN, SONNY PEARCE, AND GAVIN STARR-THOMAS

Department of Human Movement Studies
The University of Queensland
Q. 4072
Australia

Abstract

Swimmers appear to dissipate heat mainly through conduction and convection. However, if the water is warm, metabolic heat may accumulate, and fluid lost through the increased role of sweating. Competitive swimming involves training of both long duration and high intensity yet fluid loss in swimmers has yet to be empirically examined. The purpose of this study was to examine the body mass changes of swimmers during a typical endurance swim training session. Five high-performance male swimmers (19-39 years) volunteered for the study. Testing took place at an indoor 25-meter swimming pool with water temperature, air temperature and relative humidity 26.5°C, 20.5°C and 82%, respectively. Body mass was measured before and after a 4700m swim training session during which fluid intake was nil. The major finding of the current study was a significant decrease ($p<0.01$) in body mass following the training session. It appears that high intensity endurance swim training leads to significant weight and fluid loss in well-trained male swimmers. The results of the current investigation strongly suggest the importance of swimmers consuming liquid before, during and following a swim training session.

INDEX TERMS: Swimming, Dehydration, Endurance, Body Weight, Sweat, Fluid Loss, Training

Introduction

Metabolic heat from physical activity may be lost from the body via radiation, conduction, convection, or evaporation (1). The degree to which each of these mechanisms contributes to heat loss is dependent upon both environmental temperature and humidity, fluid velocity, and both exercise duration and intensity (2). In water, swimmers appear to dissipate heat mainly through conduction and convection if the water is cool enough (2). However, if the water is warm, the temperature gradient between the body and the water is reduced and metabolic heat may accumulate. Fluid could therefore be lost in swimmers through the increased activation of the sweat response.

Sweat rate during exercise of long duration typically ranges from 1.0-1.5L/h but this rate may be increased in physically-trained or acclimated subjects (3). Indeed, elite marathon runners have reported fluid losses of up to 3.7 litres per hour during competition in hot and humid ambient conditions (4). Together with water, electrolytes such as sodium are lost via sweating.

Fluid loss, particularly in endurance athletes such as distance swimmers, may also take place through breathing. In physically active persons, 2-5 ml of water are lost from the respiratory tract each minute during strenuous exercise (5). This may be a significant fluid and weight loss over a long and intense swim training session. Dehydration due to fluid loss through both the respiratory tract and sweating leads to changes in blood volume and electrolyte imbalance which may in turn may cause a reduction in physical work capacity.

Water provides the medium for energy metabolism within muscle cells and is essential for maintenance of an adequate blood volume. During prolonged exercise there is a continuous loss of total body fluids from within the blood and both the intra- and extracellular fluids. In the absence of fluid ingestion, this fluid loss is associated with a progressive reduction in total body water and body weight (6).

The effects of hypohydration on athletic performance are well documented in runners and cyclists (7). Swimming is an activity not generally associated with dehydration or heat stress. However, swimming is a physical activity often involving training of both long duration and high intensity, particularly for the endurance swimmer or triathlete. Such training may last up to two hours, often at high intensity, and often in warm water and in both hot and humid environmental conditions. Researchers at the International Centre for Aquatic Research in Colorado have observed that body temperature becomes elevated during three hours of swim training. Furthermore, the observed increase in core temperature was associated with a decrease in blood volume which elevated heart rate during training (8). While a number of previous reports have discussed the importance of fluid replacement in swimmers (8, 9, 10, 11), to our knowledge, fluid and weight loss in swimmers has yet to be empirically examined. The purpose of this preliminary study

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was to examine the body weight changes of five high performance swimmers during a typical endurance swim training session.

Methodology

Subjects: Five male subjects between 19 and 39 years volunteered for the study (Table 1). Each subject had both a minimum of 10 years competitive swim experience and was ranked in the top 10 in the state of Queensland for triathlon, still-water swimming, masters swimming, or lifesaving.

Table 1. Subject characteristics

Subject	Age (yr)	Body Mass (kg)	Height (cm)	Skinfold Σ (mm)*
1	27	72.2	178.0	59.3
2	25	71.9	177.0	54.4
3	20	71.5	178.5	49.4
4	39	89.0	182.5	111.5
5	24	62.4	172.5	48.2
Mean	27.2	73.4	178.0	64.6
SEM	3.2	4.3	1.6	11.9

*Sum of eight skinfolds

Procedure: Testing took place at an early morning (5.30am) training session within an indoor 25-meter swimming pool. Water temperature, ambient temperature, and relative humidity were 26.5°C, 20.5°C, and 82%, respectively. As a measure of subcutaneous fatness, skinfold measures (mm) were taken by a trained anthropometrist using John Bull Calipers at eight sites (biceps, triceps, subscapular, mid-axilla, suprailiac, abdominal, thigh, calf). Body mass was measured to 0.1kg using a calibrated beam balance scale (Mercury, model 211FP) and the subjects nude. Each subject was encouraged to consume a normal meal and fluids the evening prior to testing. No fluids or solids were consumed the morning prior to testing and each subject had voided both bladder and bowels prior to the initial weigh-in and swim session.

A typical high-intensity endurance swim session was then undertaken. The session was developed and supervised by a Level II swim coach (G. S-T) and consisted of a 1300m mild-to-moderate warm up, a 3000m main set (30x100m freestyle on 1m 40s time base), followed by a 400m swim down. The intensity of the main set was monitored at regular intervals using a Polar heart rate monitor. The intensity of the 100m swims was kept within 10-20 heart beats of previously determined individual maximal heart rates. During the training session, food and fluid intake was nil and any urine loss was collected and measured. Immediately following the swim session, each subject was asked to towel completely dry, blow dry both the body and head hair, and reweighed nude.

Statistical Analysis: Descriptive data (± SEM) were determined for age, height, skinfold totals, and pre- and post-training body masses. A Students t-test for repeated measures was undertaken to compare body mass before and after the swim training session. Statistical significance was accepted at the 0.05 level.

Findings

The major finding of the current study was that a significant decrease ($t=6.7$, $df=4$, $p<0.01$) in body mass was observed following the high intensity swim training session. Table 2 shows the body mass of each subject before and after the high intensity swim training session.

Table 2. Individual changes in body mass following swim training

Subject	Mass Pre (kg)	Mass Post (kg)	Δ Mass (kg)	Δ Mass (%)
1	72.2	71.7	0.5	0.7
2	71.9	71.3	0.6	0.8
3	71.5	71.0	0.5	0.7
4	89.0	87.9	1.1	1.2
5	62.4	61.6	0.8	1.3
Mean	73.4	72.7*	0.7	0.9
SEM	4.3	4.2	0.1	0.1

*Significantly different from pre-training body mass ($t=6.7$, $p<0.01$)

Discussion

The purpose of this study was to examine the body mass changes of five high performance swimmers during a typical endurance swim training session. While it is acknowledged that the number of subjects is small, to the authors' knowledge the current study is the first to observe possible fluid loss following high intensity swim training. The significant change in mean body mass was 0.7 kg, or 0.9 percent of the pre-training body mass. While a 2-3% decrease in body mass has been suggested to lead to performance decrements in athletes (12), earlier work suggested that fluid ingestion equal to the rate of sweating was more effective in maintaining core temperature and exercise performance than voluntary or partial fluid replacement (13). A recent study has suggested that dehydration lead to linear increases in core temperature by approximately 0.15°C for each one percent decrease in body weight when exercising in the heat (14). While core temperature was not measured in the present study, increased core temperature accompanying dehydration has previously been shown to lower sweat rate and thus the potential for heat loss through sweat evaporation (14).

It is also possible that some of the body mass loss reported in the current study may have been due to substrate utilization (glycogen, fat). It has been estimated that 3-4g of water is bound with each gram of glycogen (15) and that increased glycogen usage occurs during exercise of increasing intensity such as that undertaken in the present study (15). Previous reports (6, 16) reported a substantial decrease in intracellular water content of skeletal muscle following high intensity endurance training of similar duration to that used in the current study. It is thus possible that the loss of intracellular water may be the result of water released with the breakdown of muscle glycogen and a shift of water from the intracellular to extracellular space. Furthermore, it might be suggested that exercise-induced dehydration in a warm environment may result in intracellular water loss which may decrease exercise performance if fluid replacement strategies are not in place.

Applications

A number of previous studies have reported decreases in both aerobic and anaerobic performance following exercise-induced dehydration in hot environments (7). Anaerobic performance appears more likely to be reduced if dehydration is due to both exercise and heat exposure (17). It appears that electrolyte imbalances and elevated body temperature accompanying exercise-induced dehydration reduce anaerobic performance (7). Dehydration may also lead to increased muscle temperature and elevate muscle acidosis, thus inhibiting the glycolytic pathway and anaerobic performance (18).

Numerous studies have also observed decreased aerobic performance following dehydration in a variety of sports (19, 20). Dehydration may be associated with a decreased plasma (blood) volume which in turn increases blood viscosity (21). A viscosity-mediated increase in resistance to blood flow and reduced heart filling pressure may reduce stroke volume and cardiac output during maximal swimming although the heart rate may increase to maintain both cardiac output and blood pressure during submaximal swim intensities. The implication for swim coaches is that heart rate at a given submaximal speed or intensity may become higher due to the extra heat load placed on the body.

If a swimmer is both heat stressed and dehydrated, aerobic performance may further be compromised. The combination of exercise and heat stess results in competition between the central and muscular circulation for a limited blood volume. In hot and humid conditions, the superficial skin blood vessels dilate to increase skin blood flow so as to allow heat dissipation. This increased superficial blood flow may reduce maximal aerobic power by reducing the proportion of blood getting to the active muscles or by reducing central blood volume, venous return, and cardiac output. Swim performance may again be compromised.

The results of the current investigation strongly suggest the importance of swimmers consuming liquid before, during and following a swim training session. The American College of Sports Medicine (22) recommends athletes drink at least 100-200 ml (approx. three mouthfuls = 100ml) per 10-15 minutes of running. In swimmers, this would involve drinking after and during the warm-up, during the main set, after the main set and during the cool down. Drink bottles need to be kept accessible and ideally in a cool place (e.g. the shade of the blocks) since cooler fluids have been shown to be absorbed more quickly than warm fluids.

In hot and humid conditions coaches would also be advised to weigh swimmers before and after training (1kg weight loss = 1L fluid loss) in order to measure how much fluid swimmers are losing. While water has been shown to be adequate for fluid replacement in events or training less than 45-60 minutes in duration, research has shown that the body absorbs fluid containing 6-8 percent (6-8g/100ml) carbohydrate and sodium (approx 0.05g/100ml) much faster than using water alone (23).

The current study was undertaken using an 80-minute training session in an indoor facility during the winter months (June) in Queensland, Australia. Typical peak season training sessions may be longer in duration and possibly swum in both higher pool and air temperatures. The warmer the water and air temperature, the greater the potential for dehydration and thus decrements in swim training performance. These factors may lead to greater fluid loss than that reported in the current study.

In conclusion, it appears that high intensity endurance swim training leads to significant weight and fluid loss in well-trained male swimmers. While it is yet to be determined whether the observed fluid deficit leads to elevated body temperatures, decreased blood volumes, electrolyte imbalances, or decreases in swim training performance, fluid replacement is strongly recommended during high intensity swim training sessions. Furthermore, it is recommended that coaches in hot and humid environments or warm pools should weigh their swimmers before and after swim training sessions and adjust fluid intake if fluid deficits are observed.

Address for correspondence: Peter Reaburn, Department of Human Movement Studies, The University of Queensland, Q. 4072, Australia. Phone: + (07) 365-6851, Fax: (07) 365-6877; e-mail: peterr@hms01.hms.uq.oz.au

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Force Plate and Video Analysis of the Tumble Turn by Age-Group Swimmers

B.A. BLANKSBY, D.G. GATHERCOLE, AND R.N. MARSHALL

Department of Human Movement
The University of Western Australia
NedlandsWA 6907
Australia

Abstract

Using a force plate and two underwater video cameras, the features of a tumble turn by 17 male and 19 female swimmers of similar age (13 years ± 9 mths), swimming experience, height (156.7cm ± 3.96cm) and mass (46.3 ± 5.47kg) were studied. The subjects completed 3 x 50m maximum effort freestyle swims in a 25m pool leaving on a 3 minute departure time.

Discriminant analysis revealed no gender differences. The 5m round trip time (RTT) correlated significantly with peak force, wall contact time, impulse, tuck index, turn start time, swim resumption distance and peak speed. Stepwise regression found the best predictors of 5m round trip time (RTT) to be peak force, swim resumption distance, turn start distance and height. ANOVA comparisons of fastest 33% v slowest 33% revealed significant differences between the 50m, 5m and 2.5m RTT; wall contact time, peak force on the wall, peak outgoing speeds, and the turn start distance

INDEX TERMS: Peak force, flip turn, swimming, freestyle

Introduction

During the tumble turn one is trying to reverse the direction of the body in the shortest amount of time and regain the same or increased speed in the opposite direction. The percentage of time taken in turning has been found to range from 21% in a short course 50 yard freestyle to 33% of race time in short course events of 200 yards or longer (12,18). In the longest freestyle events for men (1500m) and women (800m), the average speed after push-off was found to be significantly and positively correlated with event time and order of finish (5).

Only two studies have used a waterproof stainless steel force platform to measure the force generated on the wall during swimming turns (16,17) Results showed that the mean impulse for the tumble turn by trained swimmers was greater than that of the recreational swimmers. The average time on the wall for the highly trained swimmers also was less than that of the recreational swimmers (17).

Toussaint et al. (19) found no change in drag over a 2.5 year growth period of young swimmers. It was concluded that, although body mass and cross sectional area had increased dramatically, the greater height measures had masked the increase in resistance caused by form and wave drag. It would appear that height could play a major role on the amount of drag experienced (9,21). Hence, the subjects in this study were chosen to be of similar height and mass to minimise these effects.

Because little objective data are available and turning plays an important role in competition, it was deemed valuable to examine selected kinetic and kinematic features of the freestyle tumble turn by age-group swimmers.

Methods

Subjects were chosen with similar age, height and mass characteristics (1,2) to minimise variations in the coefficient of drag due to anthropometric effects (6,9,19). The subjects had participated in swimming training for at least three years and attended training for three sessions of 1.5 hours each per week. The group comprised 17 males of mean height, 157.27 ± 4.32cm; mass, 46.56 ± 4.94kg; and age, 141.18 ± 9.7-months; and 19 females of mean height 156.18 ± 3.64cm; mass, 46.05 ± 6.03kg; and age, 143.37 ± mass, 46.56 46.56 = 4.94kg; and age, 141.18 = 9.7months; and 19 females of mean height 156.18 = 3.64cm; mass, 46.05 = 6.03kg; and age, 143.37 = 8.47months. Trochanterion height was measured (ie. from ground to superior border of greater trochanter of femur). Each subject warmed up thoroughly prior to the testing protocol of 3 x 50m maximum effort freestyle swims in a 25m pool on a 3 minute departure interval.

One video camera was placed underwater, 10m to the side of the swimmer and 5m in from the turning surface. A second camera was placed underwater, 8m to the side of the swimmer and 2.5m in from the turning surface (See Figure 1). Both cameras were 0.2m beneath the water surface. A 5m

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long scaling device, with markings every 0.1m, was placed directly beneath the swimmer.

Force, time and impulse data were obtained using a waterproof force platform attached to the end wall. The force platform was designed by technicians in the Human Movement Department at the University of Western Australia. It was constructed of two stainless steel plates, each with dimensions of 500mm x 500mm x 12mm. The two plates were separated by 20mm cylindrical posts with the force transducers (strain gauges) mounted at the four corners of the plates (3). The force plate was fixed in place with hooks over the pool edge and into the drain gutters.

Kinematic data were collected from a frame by frame analysis of the videotape (50Hz) via a grid screen. The vertex of the head was used as the marker point for distances travelled; the trochanteric height was the marker for assessing the amount of tuck. Kinetic data were collected from the force platform via an AP30 computer system. Measures recorded were:

1. Total 50m swim time;
2. Time of 5m and 2.5m RTT.
3. Contact time of the feet with the turning surface.
4. Peak force exerted perpendicular to the wall.
5. Impulse exerted on the wall during the turning motion.
6. Peak outgoing speed.
7. Degree of maximum tuck when the feet are on the wall during the turn. This was defined as the point when the hip was at its minimum distance from the wall expressed as a percentage of the trochanteric height (tuck index).
8. Distance from the wall that the head commenced moving downwards into the turning motion (Turn start distance).
9. Distance out from the wall that stroking recommenced after the turn (Swim resumption distance).
10. Speed at the resumption of stroking after the turn (Swim resumption speed).

Statistical Analysis

While the total 50m race time is the ultimate test of performance, this study sought to examine turning performance. Because the 50m swim time includes some advantage from the first few metres at the start and the effects of fatigue over the final few metres, it was considered that using the 50m RTT could mask some aspects of the turn. The 2.5m RTT most closely incorporates the turning motion but does not completely encapsulate the results emanating from the time spent on the wall. For example, the peak speed, swim resumption distance and speed would require a greater distance to be included. Hence, the 5m RTT was chosen as the most appropriate distance over which to study turns. Apart from this distance incorporating the aspects of the turn being studied, it also has a practical advantage for coaches, due to them being able to use the backstroke flags to assess turning drills (15).

Each subject's fastest 5m swimming RTT was chosen for statistical analysis.

1. A Discriminant analysis ($p<0.05$) was conducted to ascertain whether any significant differences existed between the male and female groups.
2. A Pearson correlation co-efficient matrix was constructed to identify the relationship between variables.
3. A multiple stepwise regression analysis was then conducted using the 5m RTT as a dependent variable to determine the overall predictive characteristics of the variables and to remove those variables that were not predictive. The multiple regression provided beta weights which enabled the relative importance of each component to be derived.
4. Finally, an ANOVA ($p=0.05$) was carried out on the averages of the fastest 33% versus the slowest 33%, 5m RTTs. This was an attempt to more clearly identify and differentiate factors contributing to a faster tumble turn.

Results

A discriminant analysis revealed no significant differences ($p<0.05$) for the 5m RTT between the 17 males and 19 females. Hence, all the subjects were pooled into one group with a sample size of 36. The means and standard deviations for all data are reported in Table 1.

Table 1: Group means and standard deviations for individual variables.

Measured Variable	Mean ± Standard Deviation (n = 36)
Height (cm)	156.7 ± 4.0
Mass (kg)	46.3 ± 5.5
Age (months)	142 ± 8
50m swim time (s)	38.64 ± 3.39
5m RTT (s)	7.66 ± 0.79
2.5m RTT (s)	3.70 ± 0.47
Peak Force (N)	693.4 ± 228.1
Wall Contact Time (s)	0.58 ± 0.2
Impulse (Ns)	177.2 ± 50.2
Tuck Index (%)	56.6 ± 17.2
Turn Start Distance (m)	0.62 ± 0.18
Swim Resumption Distance (m)	2.51 ± 0.58
Peak Speed (m/s)	2.05 ± 0.29
Swim Resumption Speed (m/s)	1.35 ± 0.24

A correlation matrix was established to investigate the strength of the association between the variables (Table 2). As the subjects were chosen from within one standard deviation of the mean height and mass for their age (1, 2), and had not influenced the discriminant analysis, these measures were not included in the correlation matrix. A significant, positive correlation was found between the 5m RTT and wall contact time; while significant, negative correlations were found

Table 2: Pearson Product Moment Correlation matrix determining strength of relationship between variables

	50m Time	5m RTT	2.5m RTT	Peak Force	Time on wall	Impulse	Tuck Index	Turn Start Time	Swim Resumption Distance	Peak Speek	Swim Resumption Speed
50m Time											
5m RTT	0.90*										
2.5m RTT	0.72*	0.84*									
Peak Force	-0.52*	0.59*	0.54*								
Time on Wall	0.45*	0.53*	0.69*	0.39*							
Impulse	-0.29*	0.31*	-0.27	0.64*	0.02						
Tuck Index	-0.36*	0.49*	0.54*	0.39*	0.76*	0.11					
Turn Start Time	-0.41*	0.49*	0.65*	0.26	-0.71*	-0.15	0.69*				
Swim Resumption Distance	-0.36*	0.49*	0.57*	0.24	-0.40*	0.29*	0.32*	0.31*			
Peak Speed	-0.41*	0.50*	0.49*	0.39*	-0.24	0.55*	-0.03	0.18	0.65*		
Swim Resumption Speed	-0.12	-0.06	0.14	0.29*	0.26	0.08	-0.16	-0.25	-0.52*	-0.18	

*Denotes significance (<0.05)

between the 5m RTT and peak force, impulse, tuck index, turn start time, swim resumption distance and peak speed. No significant correlation existed between the 5m RTT and swim resumption speed.

A stepwise multiple regression was conducted to seek the best possible predictors of the 5m RTT. Significant independent variables were added to the model when a variable was determined to add predictability to the regression equation at $p<0.05$. Higher beta weight scores indicated that they are more predictive of the dependent variable. The results of the stepwise regression for 5m RTT (see Table 3) indicated that the best predictors in order of importance were: peak force, swim resumption distance, turn start distance and height. These variables accounted for 55% of the variance ($r = 0.775$).

Table 3: Stepwise regression results for prediction of 5m RTT

Variable:	Regression Coefficient	Beta Weight	Multiple Correlation	Adjusted R-squared
1. Peak Force	-0.160	-0.472	0.593	0.333
2. Swim Resumption Distance	-0.302	-0.220	0.693	0.449
3. Turn Start Distance	-1.384	-0.313	0.738	0.502
4. Height	-0.049	-0.247	0.775	0.549
Constant:	18.115			

A regression equation then was developed to predict the 5m RTT for age-group freestylers of similar size and experience.

5m RTT = 18.115 -0.160 Peak Force - 0.302 Swim Resumption Distance - 1.384 Turn Start Distance - 0.049 Height.

The fastest 33% of the performers for the 5m RTT($\overline{x}$ = 6.76s) were compared with the slowest 33% of performers ($\overline{x}$ = 8.50s) using an ANOVA ($p<0.05$) (see Table 4). Significant differences ($p<0.05$) were found between the two groups for the 50m, 5m and 2.5m RTTs; and peak force, wall contact time, turn start distance, swim resumption distance and peak speed. However, no significant differences were found between the 5m RTT and impulse, tuck index and swim resumption speed.

Table 4: Comparison of group Means (± SD) of fastest 33% performers vs slowest 33% of performers using 5m RTT as the dependent variable.

	Fastest 33%	Slowest 33%	Difference
50m (s)	35.61 ± 2.68	41.82 ± 1.97	-6.21*
5m RTT (s)	6.76 ± 0.40	8.50 ± 0.18	-1.74*
2.5m RTT (s)	3.22 ± 0.33	4.18 ± 0.14	-0.96*
Peak Force (N)	80.500 ± 223.67	548.48 ± 167.16	252.02*
Contact Time (s)	0.47 ± 0.16	0.73 ± 0.21	-0.26*
Impulse (Ns)	185.51 ± 52.29	160.69 ± 26.88	24.82
Tuck Index	62.70 ± 19.05	49.28 ± 15.57	13.42
Turn Start Distance (m)	0.75 ± 0.17	0.54 ± 0.14	0.21*
Swim Resumption Distance (m)	2.77 ± 0.56	2.16 ± 0.31	0.61*
Peak Speed (m/s)	2.17 ± 0.21	1.85 ± 0.21	0.32*
Swim Resumption Speed (m/s)	1.36 ± 0.21	1.36 ± 0.26	-0.02

Discussion

Impulse is related to the change in speed produced by the swimmer while in contact with the force platform. The mean impulse recordings were 177.2 ± 50.2 Ns, with a minimum of 73.3 Ns and a maximum of 305.3 Ns. These values are similar to earlier studies (16,17) which reported values of 217

± 28 Ns and 262.7 ± 53.8 Ns, respectively. The impulse values are slightly higher in the previous studies but the differences can be attributed to the anthropometric characteristics of the subjects. The strength, size, speed and skill component in turning affects the magnitude of the impulse that a swimmer derives from the turning surface during a freestyle swimming turn. Because impulse is affected by both time and force, it is difficult to relate this variable precisely in turning.

The high correlations between the 5m RTT and the 50m swim time (0.9), and 2.5m RTT (0.72), reinforce the importance of turning in swimming performance. Mean wall contact time in this study was 0.58s, and ranged from 0.26s to 1.10s. This was similar to the mean recorded by Nicol and Kruger (16) who found an average contact time of 0.51s for 5 trained university swimmers. The mean contact time for the six swimmers in the Takahashi et al. (17) study was 0.42s. However, their 3 highly trained swimmers recorded a mean contact time of 0.36s whereas the 3 recreational swimmers recorded an average of 0.48s (17). This longer wall contact time for the recreational swimmers is of a similar magnitude to the present study, and that by Nicol and Kruger (16). The differences in wall contact time support the notion that the highly trained male adult athletes developed greater muscular force with a shorter time on the wall than recreational, female or adolescent swimmers.

The mean peak force for the 36 swimmers was 693.35 N and ranged from 335.3 N to 1217.42 N. The significant differences ($p<0.05$) found for peak force and wall contact time were reinforced by comparing the fastest 33% of the performers with the slowest 33% on the basis of 5m RTTs. The swimmers with faster times demonstrated significantly higher peak forces and decreased wall contact times. Despite impulse being the product of force and time, some high jumpers have demonstrated decreased time of contact with the ground at take-off while creating greater impulses (4,11). It was thought that the jumpers were using elastic energy efficiently to create a higher impulse despite the decreased time. It is possible that swimmers could utilise a similar phenomenon in a horizontal direction but further evidence is required to substantiate this.

The stepwise multiple regression found that peak force was the best predictor of the 5m RTT, accounting for 33% of the variance. The data suggest that, to achieve fast 5m RTTs, subjects need to increase the impulse which results from an increased peak force applied to the turning surface, but decrease the amount of time in contact with the wall. These results support the conclusions of Miyashita et al. (14) that an increase in muscular power is important to shorten the time spent turning and that some form of resistance training was required to develop greater push-off forces. The peak force benefit is more fully exploited in the 5m RTT which it helps decrease. For example, the mean wall contact time of 0.58s represents approximately 15.7% of the mean 2.5m RTT, but 7.5% of the mean 5m RTT. Thus, it represents a double proportion of non-swimming time in this mean time period of 3.70s.

There must be a position where the combination of distance from the wall, time spent on the wall, force exerted on the wall, distance to be swum and body streamlining are optimal. For example, a swimmer with a tuck index of 1.0 has either missed the wall or has the legs fully extended and cannot push off. It would be equally undesirable to assume a tightly bunched-up position requiring a long and sustained push-off from a poorly streamlined position. This latter position could be likened to performing a vertical jump with a counter movement. By dipping too low, one has to work through a range of motion which is not effective in producing force.

Swim resumption distance was the second factor in the stepwise regression. A significant correlation also was found between the swim resumption distance and tuck index ($r = 0.69$). That is, the further the swimmer is away from the wall at push-off, the further out does stroke resumption begin. One would have to assume that all other factors need to be equal for this to occur. For example, swim resumption distance is affected by the ability of the swimmer to adopt and maintain a streamline (10); and the conscious decision of choosing the point at which to resume stroking.

After the turn, swim resumption distance was measured as the initial movement of the hand from the glide position. The mean stroke resumption distance was 2.51 ± 0.58m, and varied between a minimum of 1.70m and a maximum 3.90m. This was a lesser mean distance than was found by Chow et al. (5) who recorded a mean stroke resumption distance of 4.06/4.84m for females/males across all freestyle events from 100m to 1500m. Again, these differences can be attributed partially to the glide distance measurement techniques, the anthropometric characteristics and skill level of the swimmers used in each study.

Swim resumption distance was negatively correlated with 50m ($r = -.36$), 5m ($r = -.49$) and 2.5m ($r = -.57$) RTTs. The strength of the relationship increased as the distance decreased and suggests effective use of the increased speed from the push-off phase of the turn. Swim resumption distance also showed a strong, positive correlation with peak speed. The data indicate that an increased speed off the wall enables one to hold the glide further. Hence, one needs to maximise speed off the wall but resume swimming before reaching race pace. A significant, negative correlation also existed between the swim resumption distance and the swim resumption speed. Swimmers who glide too long after push-off will decelerate to less than the average swimming speed, and require additional time and energy to regain race speed. On the other hand, when stroking is commenced too early, the swimmer does not fully use the potential speed advantage gained via maximising the propulsive force from the wall.

Swim resumption speed was not significantly related to the 50m, 5m and 2.5m RTTs. However, there were significant negative relationships with the stroke resumption distance and a significant, positive correlation with the peak force applied to the turning surface. These results suggest that some swimmers are gaining an advantage from the turn. Those with an increased peak force on the wall have a higher swim speed at resumption of stroking. Due to the increased speed off the wall, the stroke resumption distance is increased. This could enable the swimmer to maintain a speed higher than race pace for a longer duration. It therefore becomes critical to use wisely the added speed off the wall to reduce 50m, 5m and 2.5m RTTs.

The average swimming resumption speed after the turn was 1.35 ± 0.24m/s. The swimmer recording the minimum swim resumption speed (0.88m/s) approached the wall at 1.11m/s. By allowing the speed off the wall to decrease to 0.88m/s, she lost some of the push-off benefit by resuming swimming too late. On the other hand, the swimmer with the highest swim resumption speed (1.87m/s) approached the wall at 1.06m/s. Thus, resuming swimming at 1.87m/s was too early to have gained the push-off benefits.

Similarly, the longest glide after the push-off was 3.9m by a swimmer who approached the wall at 1.55m/s. The speed at swim resumption was 1.2m/s and the swimmer had waited too long. The shortest glide recorded was 1.7 m by a swimmer who approached the wall at 1.25m/s. This person resumed swimming at 1.3m/s which was quite appropriate. These examples demonstrate the importance of the swimmer being able to feel the best point at which to resume swimming after the turn.

Chow et al. (5) reported values for outgoing swim speeds for men's freestyle events that were 2.44 ± 0.14m/s (100m), 2.54 ± 0.14m/s (200m), 2.40 ± 0.13m/s (400m) and 2.37 ± 0.11m/s (1500m) respectively. For the women's freestyle events, the average speed out from the wall was 2.22 ± 0.18m/s (100m), 2.37 ± 0.21m/s (200m), 2.26 ± 0.20m/s (400m), 2.23 ± 0.17m/s (800m) respectively. These values for elite swimmers were considerably faster than the swimming resumption speed of the age-groupers in this study and that found by Nicol and Kruger (16). As well as the Chow et al. (5) subjects being elite athletes, the average speed out was taken from the wall to the completion of the first stroke. This technique differs from the present study which determined the swim resumption speed across a distance of thirty centimetres prior to the commencement of stroking. This differed again from Nicol and Kruger (16) who measured the time taken to travel from three metres to six metres from the wall as an average speed out.

The third factor in the stepwise regression was the turn start distance. When comparing group means based on the 5m RTTs, it is evident that, if the turn commences a greater distance out from the wall, the times are faster. The turn start distance was 0.62 ± 0.18m and ranged between 0.35m and 1.00m. This compared to 2.04m for elite male swimmers across 100m, 200m, 400m and 1500m freestyle events; and 1.84m for elite female swimmers across the 100m, 200m, 400m and the 800m freestyle events reported by Chow et al. (5). The differences in this study could be attributed to the fact that children were used as subjects and the different method of determining the distance out from the wall. Chow et al. (5) measured the horizontal distance between the vertex of the head of the swimmer and the wall at the instant the swimmer's forward hand entered the water during the last stroke before initiating the turn. The present study used the distance between the vertex of the head and the wall when the head commenced moving downwards in a vertical plane. Future studies should adopt standard procedures for easier comparison.

Peak speed off the wall was correlated with all three time measures ($p<0.05$). The correlation was negative because the higher the peak speed off the wall, the less were the 50m, 5m and 2.5m RTTs. When the fastest and slowest 33% of performers in the 5m RTT were compared for peak outgoing speed, significant differences were obtained ($p<0.05$). The ability of a swimmer to produce higher peak speeds off the wall reduced the 50m time.

The tuck index was negatively correlated ($p<0.05$) with the three RTT measures. This suggests that the larger the tuck index (ie. straighter legs), the faster will be the time. Naturally this is not so if the legs are completely straight because no muscular force could be generated. Tuck index correlations with the 50m, 5m and 2.5m RTTs suggest that the association is stronger as the RTT distance decreases. Thus, the turning component represents a higher fraction of the time and the swimming component decreases. Perhaps a higher tuck index means that the swimmer travels less distance to and from the wall to reach the designated 50m, 5m and 2.5m marks sooner. A comparison of tuck index for the top 33% of performers and the bottom 33% supported this by the better performers tending to have a higher tuck index although it was not significant ($p=0.07$). The present study cannot be directly compared to that by Ward (20) because the percentage of the tuck index which determines whether a subject is using a tuck turn or pike turn is not defined.

The fourth and final variable to contribute to the stepwise regression was height. This was an unexpected result because differences in height, mass and age were deliberately minimised. In view of the fact that they did not contribute to any gender differences via the discriminant analysis, they were omitted from the bivariate correlation. Therefore, future studies which do not attempt to eliminate body height as a contributing factor could find it to feature more prominently than in this study.

Application

Enhanced turning skill is an important component in overall swimming performance. The results of this study indicate that high peak forces and low wall contact times appear to reduce swimmers' RTTs. Coaches should recommend that swimmers approach the wall fast, rotate the body quickly and hit the wall firmly. It is possible that a fast rebound from the wall utilises elastic energy effectively (22) and leads to an increase in the peak speed off the wall. If this transfer of speed towards the wall is converted to speed off the wall during the glide phase, it will reduce swim times. Perhaps it would be advisable for coaches to implement some leg strength and power training so that peak force is increased and the time to achieve this peak force is decreased.

Swimmers should be coached to hold the glide off the wall for an appropriate length of time which optimally utilises the increased speed off the wall. If the glide is held for too long, the swimmer's speed will decrease to less than race pace, and require extra time and energy to return to that speed. On the other hand, should swimmers commence stroking immediately after they come off the wall, they will also negate the benefits to be gained from a strong push-off.

The study also suggested that starting the turn further out from the wall, or using straighter legs, may be faster. In view of the fact that height was included in the regression equation despite being minimised, the turn start distance and height could be interrelated. The use of the expression "pike turn"' needs to be defined and even renamed. If a pike dive is similar to that used by a diver, there is little movement at the hips, knees and ankles. This implies only a small degree of eccentric action of the muscles crossing these joints. Subsequently, only a small concentric force is possible when pushing off the wall. Perhaps angles >90¡ at the hip and knee in particular could be representative of tending towards a pike; and deeper angles of <90¡ be considered to tend towards a tuck turn. However, further research is necessary before this style of turn should be advocated.

Coaches can time swimmers as they pass the backstroke flags inwards and outwards from the wall. Turning technique pointers can be made and then assessed by time improvements for this 5m RTT.

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Address for correspondence: Associate Prof. B. A. Blanksby, Department of Human Movement, The University of Western Australia, Nedlands WA 6907, Australia. Phone: 61 9 3802361, Fax: 61 9 3801039.

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DAVID A. TANNER

Indiana University
Bloomington, Indiana

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.

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Address for correspondence: David A. Tanner, M.S., Human Performance Laboratories, Indiana University, Bloomington, IN 47405-4801

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1. Hand acceleration may increase propulsive drag above quasi-steady values by as much as ____________ %.
2. When Newton's second law is applied to the hand moving through the water, two masses must be considered. What are they? ______________________________
3. The propulsive drag and lift forces developed by a swimmer's hand at a given time are dependant upon the size, orientation, shape and velocity of the hand at that time, but also ______________________________

"Swim-training profiles"

4. In the present study, three variables appeared as the most fatiguing in the short term. They were ______________________________
5. The test which entailed swimming repeat 200 m at progressively increasing velocities was designed as a measure of ______________________________
6. The time to reach peak performance during supercompensation ranged from between ________ and _____ days.

"Analysis of the tumble turn"

7. In the short-course, 50-yard freestyle, the percentage of time taken in turning has been estimated to be as much as ______________
8. The two most important variables in reducing RTTs are ______________ and ______________.
9. The study suggests that turning further from the wall and or ______________________________ may also improve turn time.

"Recovery from maximal swimming"

10. In this study, how long did it take to remove half of the blood lactate following the exercise bout? ______________
11. What do the initials IOBLA stand for? ______________________________
12. What workload appears to be most effective in removing lactic acid from the blood? ______________

"Fluid Loss"

13. Sweat rate during intensive activity can range from ________ to ________.
14. Dehydration may lead to increased muscle temperature and increase acidosis, thus inhibiting ____________ and ______________.
15. Following the 80-minute work bout, how much weight was lost? ______________

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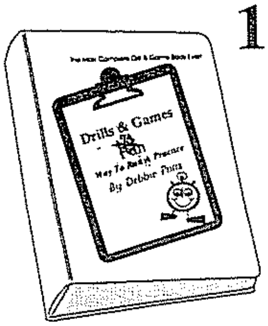

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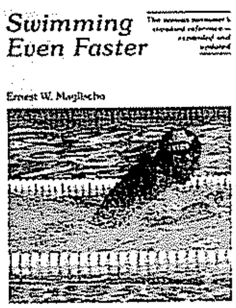

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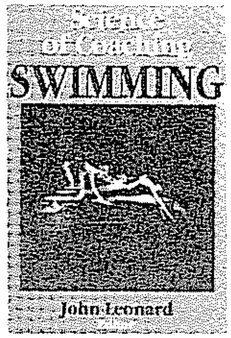

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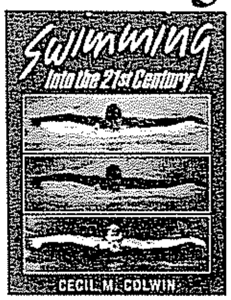

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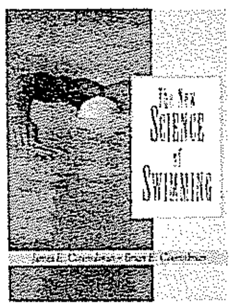

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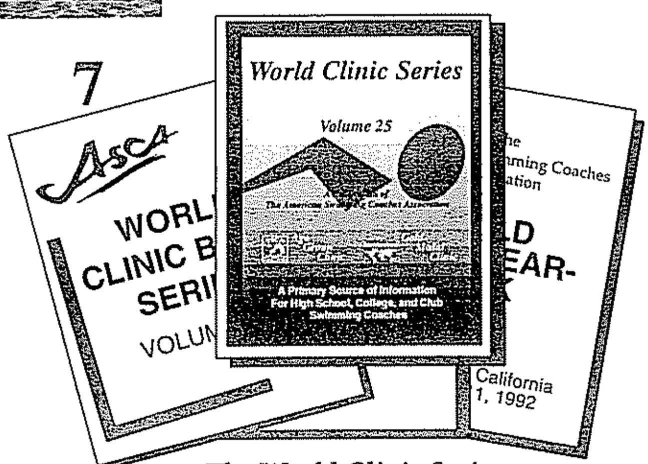

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Joel M. Stager, PhD, FACSM
Editor-in-Chief
The Journal of Swimming Research
Associate Professor
Director, Human Performance Laboratories
Dept. of Kinesiology, Indiana University
Bloomington, IN 47405-4801
Phone: 812-855-1637 Fax: 812-855-9417
e-mail: stagerj@indiana.edu

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