THE JOURNAL OF
SWIMMING RESEARCH

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The Art and Science of Swimming

In 1940, Frances Greenwood compiled a list of references pertaining to swimming and entitled it “Bibliography of Swimming.” Included within this text are no fewer than 10,000 cross-referenced titles, each complete with a brief abstract. In my mind, this is simply an amazing effort in that the author compiled these titles prior to the existence of WordPerfect, CD ROMS, on-line literature searches and the likes. Wow! If you didn’t already have a summer reading list prepared, here is a great place to start.

Within Greenwood’s bibliography through June of 1938, there were nearly 40 texts entitled “The Art of Swimming” and only three with some variant of “The Science of Swimming.” To my surprise, Doc Counsilman’s landmark 1968 work “The Science of Swimming” was actually the third book to be entitled this way. It appears that a certain J. Frost beat Doc for the first place gold medal by some, oh, 152 years when he published his text “Scientific Swimming.” While not exactly the same, for the sake of argument, it is close enough. A Mr. Frank Sullivan placed second in this contest by using the more familiar title “The Science of Swimming” in 1928. Finally after another 40 years... well, I guess you already know who came in third.

My point is not so much that Doc’s book was only the third to define science’s role in swimming, but rather, that over the years, art seems to have been the driving influence in swimming as compared to science by more than ten to one. It is this fact that truly troubles me.

Though Greenwood identifies the first written work on swimming to have been published in 1638, it can be argued that competitive swimming is essentially one hundred years old, give or take a few years either way. For the first half of this century, very little progress took place in terms of the training of swimmers. Most advances in swim performance came about as a result of changes in stroke mechanics and improvements in stroke techniques. It was not until the 1950s that any systematic search for a means to improve physiological conditioning of swimmers was begun. I’d like to say that the search was begun by scientists. It wasn’t. I’d like to say that the scientists played a big role. They didn’t.

While there have been scientists interested in human performance and sport science since the early decades of this century, the bulk of the research on these topics has taken place in the last 35 or 40 years. What initially drove this research was an interest in understanding the design criteria of the body, in other words, the limits of human performance based upon the functional capacities of the various tissues, organs, and systems. This was not with the intent of obtaining gold medals, rather, with the intent of determining how to keep soldiers soldiering and workers working. When the masses began to run and the marathon became “The Marathon,” an acceleration in the science of sport was initiated. Corporations interested in capitalizing upon the fitness market quickly recognized the importance of science in product development and, of course, marketing. What they were not interested in was how to better train athletes and thus progress has been subtle, gradual and infrequent.

It is widely accepted that for big business to stay in business, a sizable amount of yearly income must be put into research and development. After attending a couple of Nationals and World Championship events, it seems pretty clear that swimming is a big business. “It takes money to make money” and “Smart money pays big dividends” are the appropriate clichés that come to mind. Following the Olympics in Los Angeles, funds became available, perhaps for the first time, for scientists in the United States to become involved in developing new training techniques and new technology for sport. It was an exciting time! Various countries throughout the world then recognized the importance of research and the rapidity of change it was capable of producing. Unfortunately, since this time, the enthusiasm for funding swimming research in the United States has gradually fallen back into the very hands that have initiated so much in the past, the coaches. Coaches are busy coaching and swimmers are busy swimming. Swimming, at least in the United States, is returning to its past as a form ‘of art’ rather than a form ‘of science.’ As an advocate of science, this troubles me and should trouble you as well.

This issue of the Journal has several interesting reports and a few surprises. Dolphins offer us a few secrets concerning hydrodynamics thanks to B. Ungerechts. D’Acquisto and associates provide an in-depth look at the velocity fluctuations apparent in the breast stroke. An evaluation of drag during streamlined is provided by Lytle and colleagues. Gehlsen discusses the serious issue of competitive starts and spinal cord injuries. The topic of taper length is explored by Kenitzer and, finally, Tanner provides us with another update of ‘In print’ which will provide you with a direction once you finish with Greenwood. Thanks are again extended to all of the associate editors, reviewers, authors and, of course, John Leonard and ASCA for their collective efforts and support.

J. M. Stager
What dolphins tell us about hydrodynamics

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Abstract

Dolphins are superbly adapted to fast swimming, and the study of how they gracefully propel themselves through water requires the interdisciplinary collaboration of zoologists, hydrodynamicists, and biomechanists. Such studies have in fact been done, and there are aspects of dolphin propulsion beyond the simple comparison to the butterfly kick that will be of interest to swimming scientists.

Although dolphins can swim three times faster than humans, they cannot deliver more power per kg of muscle mass. This phenomenal performance is made possible by a hydrodynamically optimal body shape, the oscillatory movement of the tail, and the phase coupling of the heaving and pitching of the semilunate shaped fluke. The streamlined body reduces the pressure drag to a minimum, and the combination of heaving and pitching motions transfers momentum to the surrounding water. The rate at which momentum is transferred determines the amount of thrust generated. The fluke sets water into rotation, called a vortex. Momentum is transferred and thrust is obtained either by canceling out the vortex rotation at each fluke reversal point, or by the creation of a propulsive jet from a combination of clockwise and counterclockwise vortices. Although human swimmers will not be able to set water into rotation as effectively as dolphins because of the shape and inflexibility of their ankles, this deficit can be lessened by swimmers emphasizing the reversal action of the kick, using as much as possible, a whip-like action.

Part of dolphin propulsion research has involved the examination of the water after it leaves the dolphin’s surface. Similar studies could be performed with human swimmers, using entrained air bubbles to reveal wake size or vortex formation. This would provide coaches useful feedback on how effective their swimmer’s streamline or stroke technique might be. For example, a wide wake might indicate a high drag or wasted energy spent by the swimmer “fighting” the water, rather than cooperating with it.


Introduction

Watch the graceful and seemingly effortless motion of a swimming dolphin, and you can’t help but wonder how they move so quickly through the water. Is it because they use a lot of energy, because they are so streamlined, or because they have an efficient method of propulsion? Dolphins swim correctly from birth. In contrast, we humans, who have to learn to swim, strive to achieve an optimal swimming movement and then ponder the best ways to teach this movement [1]. What can we humans, who are not adapted to locomotion in water, learn from the research that has been done on dolphins? This paper addresses that question in a manner structured according to the analysis steps used to develop an Expert System for diagnosing and advising human swimmers. This system, developed by Colman and Persyn [2], accounts for:

- Body structure, including physical parameters
- Biomechanical measuring techniques
- Movement parameters of the swimmer and of the surrounding water
- Interpretations made in relation to balance and propulsion mechanics.

Very few researchers of human swimming have attempted to visualize the water surrounding the swimmer, as is typically done during studies of dolphin locomotion. Both
dolphins and humans propel themselves by transferring momentum from their moving body parts to the surrounding water. The rate of momentum transfer, which is equivalent to the sum of external forces, determines the amount of generated thrust. In the animal kingdom, a separation of forces into propulsive and drag components cannot be made because these forces are produced simultaneously. The same phenomenon occurs in competitive swimming where, according to Brandt & Piekowsky [3], the rate of momentum transfer during self-propulsion arises entirely from the water itself. The decomposition into propulsive and braking components is not a priori "well defined" and cannot be measured separately like it is for true rigid bodies moving at constant speed. A swimmer's body changes shape continually during a stroke cycle, and the velocities of various body parts of a swimmer are highly unsteady (acceleration and deceleration occur). This complicates the fluid flow and modifies the momentum transfer between the swimmer and the water. Still, as complicated as both dolphin and human swimming may be, there are some worthwhile lessons that human swimmers can learn from the study of dolphins. This paper will explain some of those lessons.

**Study of dolphin movement**

Bottlenose dolphins, which are the ones usually studied in captivity, are of the species *Tursiops truncatus*. Table 1 compares some important characteristics of an adult bottlenose dolphin [5] and the human swimmer [authors' measurements].

Table 1. Some Characteristics of an Adult Bottlenose Dolphin and a Human Swimmer

<table>
<thead>
<tr>
<th></th>
<th>Body Length (m)</th>
<th>Body Mass (kg)</th>
<th>Surface Area (m²)</th>
<th>Span Fluke (lower arm/hand) (m)</th>
<th>Area Fluke (lower arm/hand) (m²)</th>
<th>Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolphins</td>
<td>2.7</td>
<td>228</td>
<td>2.99</td>
<td>0.68</td>
<td>0.11</td>
<td>6</td>
</tr>
<tr>
<td>Swimmers</td>
<td>1.97</td>
<td>80</td>
<td>1.83</td>
<td>0.56</td>
<td>0.09</td>
<td>1.85</td>
</tr>
</tbody>
</table>

Dolphins have a fusiform, streamlined body with a hydrodynamically favorable shape far superior to the human shape for underwater motion. The maximum diameter of a dolphin is equal to about 22% of its length and occurs at the tip of the mandible, which is about 40% along the length from its beak to the tips of its tail. In comparison, the widest part of a swimmer is only about 11% of the swimmer's length, and occurs about 24% of the way along the length from the nose to the feet. The narrow part of a dolphin's tail, just in front of the fluke, carries lateral keels and is perfectly streamlined in the plane of oscillation. The boneless fluke has a semilunate shape and possesses quite a large "aspect ratio" (ratio of fluke span to fluke area). Simple observation of the human body tells us that our feet are quite different from a dolphin's tail.

As mammals, dolphins have a warm body temperature (35-36°C), and a typical mammalian power capacity in the range of 17 W/kg muscle mass [5] to 36 W/kg muscle mass [6]. For example, jumping 2.4 m out of the water requires an exit speed of about 7 m/s and requires 30 W/kg muscle mass.

The movement of both dolphins and humans is generally recorded using the same equipment and techniques. Although air breathers and jumpers, dolphins are almost always filmed for kinematics analysis when swimming submerged, whereas humans are filmed while swimming near the water surface. Rarely do dolphins swim in a straight line along a prescribed course at a predetermined speed, which is possible for human swimmers. Consequently, the use of a three-dimensional method of filming to check the flow conditions along the body and in the wake is easier with swimmers than with dolphins.

Typical kinematics variables measured from dolphins are mean swimming velocity *u*, cycle frequency *f*, and peak to peak amplitude of the basis (or tip) of the fluke. The maximum swimming velocity that has been measured in captivity is those of human swimmers. This velocity is lower than those reported for dolphins swimming in open sea. Velocity increases with tail beat frequency, but tail beat amplitude and frequency are independent. Tail beat amplitudes don't exceed values greater than 25% of the body length. At mean cruising speed (*u* = 2.63 m/s), velocity fluctuations per cycle of about 70% have been reported for a fixed point [6]. For butterfly swimmers moving at 100 meter tempo, velocity fluctuations per cycle of about 60% occur, while for breaststokers it can be higher than 100%. These intracyclic velocity fluctuations, when related to the velocity of the center of mass, may require additional energy (beyond that for steady motion) equal to the amount of kinetic energy resulting from the difference between the lowest and highest velocity (per cycle). Although for general purposes, mean speed can be calculated by a 2D analysis of a body point, an accurate examination of the energy costs of swimming requires a 3D analysis of the movement of center of mass.

Dolphins oscillate their tail and fluke at high speeds to move through the water. This *thunniform* swimming mode (also used by sharks and tunas) is possible because of their joints, which have a high degree of freedom. This movement is different than the eel-like undulating swimming motion used by butterfly swimmers and some breaststokers, where more of the body is involved [7].

The dolphin's body oscillation, which becomes more asymmetric as speed increases (emphasizing the downbeat), can be represented by its wave parameters: period *T*, wavelength *λ*, and the resulting wave velocity *w* = *λ/T* (in the opposite direction to *u*). Ungerechts [8] has studied the wave parameters of dolphins and compared them with those of
humans. In terms of body length $L$ and time $t$, they are shown in Table 2:

<table>
<thead>
<tr>
<th></th>
<th>$u$ (m/sec)</th>
<th>$w$ (m/sec)</th>
<th>$l$ (m)</th>
<th>$T$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolphins ($n=6$)</td>
<td>3.00 m/sec</td>
<td>(2.00±0.4) L/s</td>
<td>(1.16±0.18) L</td>
<td>(0.61±0.07) s</td>
</tr>
<tr>
<td>Swimmers</td>
<td>1.28 m/sec</td>
<td>(1.55±0.22) L/s</td>
<td>(0.97±0.16) L</td>
<td>(0.63±0.07) s</td>
</tr>
</tbody>
</table>

The wave of thunniform swimmers never appears along the entire body, as it does with eels. As with dolphins, the body wave in butterfly swimmers has been shown to move backward in relation to a fixed background [9]. Note that for comparison purposes, a butterfly cycle is defined as a one upbeat kick and one downbeat kick.

In the study of dolphins, the tail beat cycle is normally divided into upstroke and downstroke, and then is further subdivided into four phases shown in Figure 1[10]. The first phase, $P_1$, starts when the base of the fluke is in line with the longitudinal axis (midline) of the dolphin body, and ends at the upper reversal point of the base (the fluke itself is still horizontal). The second phase, $P_2$, goes from the reversal point of the fluke base to the midline, and the third phase, $P_3$, goes from the midline to the lower reversal point of the base of the fluke. Finally, the fourth phase, $P_4$, goes from the reversal point back up to the midline. The tip of the fluke reaches maximum amplitude when its base is already returning toward the midline. A double joint between the peduncle and the fluke gives a large freedom of motion, and the oscillation is transferred in a whip-like manner to the fluke, which then flicks water into rotation. Water set into rotation is generally referred to as a vortex [11].

Figure 1. The delimiting positions of four phases of one tailbeat cycle, full line contours indicate the starting position per phase (adapted from [10]).

Motion of water

The displacement of water by body movement to generate thrust is determined by the size, shape and kinematics of the change in body shape. Two situations can be distinguished with swimming dolphins: gliding and self-propulsion.

Motion of water in a gliding situation

The body is rigid when gliding, and the water is set in motion relative to stationary water, affecting both the boundary layer and the external flow field. Flow visualization by means of fluorescein dye release from dolphin models has revealed that the boundary layer translates from laminar to turbulent at the point of the largest diameter [13]. Results also indicated that the velocity of the water increased from the beak to the point of the largest diameter, then decreased gradually to the tail, where it nearly came to rest, with only a small wake forming.

Gliding creates a quasi-steady situation since the speed of the rigid body is slowed mainly by viscous forces acting in the boundary layer. The effects of the relative water motion (which is partly dragged with the body in swimming direction) are as follows: The increase of velocity in the external flow field along the forebody supports laminar flow conditions in the boundary layer and low resistive forces. With decreasing velocity (point of the largest diameter) the boundary layer flow becomes turbulent accompanied by higher viscous resistive forces. This is one reason why the backward shift of the largest diameter is beneficial. The pressure drag arises from the sum of the pressure loads on the fore and aft "sides" of the body. This drag component is small because the streamline shape of the dolphins allows the hydrodynamic pressure to be nearly equal in front of and behind the rigid body (small wake formation). Due to the size and speed of dolphins, the occurrence of turbulence in the boundary layer may be beneficial, since it may better cope with the adverse pressure gradient in the boundary layer, thus delaying or preventing boundary layer separation. Separation would increase drag drastically [12].

Motion of water along an oscillating dolphin

To determine the effect of oscillation on water flow, a flexible dolphin model ($L = 0.30$ m) was studied at $u = 2.0$ m/s ($6 L/s$) with a frequency $f= 3.4$ Hz [13]. The behavior of the boundary layer was determined using a dye, and the wake flow behind the model was made visible using milk. The pressure distribution along the body was also measured.

The flow in the boundary layer was made visible by injecting dye at three points on the surface of the oscillating model. In comparison to the steady situation, the colored lines in the boundary layer showed a cyclic change of its structure. What looked like transition from laminar to turbulent flow
varied with time, showing an oscillating longitudinal shift of the boundary layer transition point. The dye lines were narrow (laminar flow) when the tail was bent to the side at which the dye was introduced and widened (turbulent flow) when the tail was bent in the direction away from the dye surface.

The effect of the oscillating tail and the phase coupling of heaving and pitching of the fluke on the wake was made visible by introducing milk into the water in front of the flexible model. The flow moved along the bending body, not separating in any phase. The development of the boundary layer along the oscillating tail may actually have been affected by the suction caused by the fluke’s action. From other published flow visualization experiments it is known "that porpoise, when viewed at night during a period when the sea contains a high concentration of phosphorescent Protozoa, leaves a very thin luminous trail" [14]. When the fluke is pitching in P2 or P4, the region behind the fluke (the trailing side) filled with milky water, creating a vortex. The vortices left behind by the forward moving dolphin remain essentially in place, indicating that water is not moved backwards very much.

Measurements of hydrodynamic pressure at the same three points where the dye was injected, revealed a smaller decrease in pressure than seen in steady flow. A change of the local pressure gradient from positive to negative (and vice versa) was seen at least once per cycle. The periodic change of flow along the body is a strong indicator of accelerated flow conditions with a strong inertial reaction on the body providing extra thrust.

The unsteady flow conditions resulting from the oscillating dolphin body are not comparable to a gliding situation. During accelerated flow, the boundary layer transition from laminar to turbulent is delayed, and the accelerating body has some increase in mass. This virtual added mass [11] might resist the deceleration of the body and try to keep it moving. The force associated with this flow, called acceleration reaction, includes a forward reaction of the fluid masses in deceleration phases of the self-propelling body. The situation can be "compared with a cyclist carrying a rucksack and being pushed in the back when braking" [2]. The reaction to the acceleration of water is becoming a relevant mechanism of propulsion in unsteady motion, wherein additional thrust (or less braking) occurs.

In order to estimate if the acceleration reaction dominates viscous effects, the Reduced Frequency S (or Strouhal number) is of some value. The Strouhal number is defined as ($FL_v/v$, which compares the time taken for a water particle to traverse the length of the body with the time to complete one cycle. If $S > 0.5$, then acceleration reaction dominates viscous forces. Typical S values are: dolphins > 0.7; humans > 1.35; and model = 0.51.

Interactive hydrodynamics

The main purpose of the body oscillation is to propel the dolphin forward. By changing its shape periodically, a dolphin transfers momentum from the moving body part to the surrounding water. The way the momentum is transferred depends on the interaction of the dolphin shape and size, and water viscosity. This interaction determines thrust, swimming speed and energy expenditure. Energy expenditure is important for all organisms, and provides a strong basis to judge experimental results in fluid biology [15].

Water is accelerated as it begins to move past a dolphin’s surface. Farther along, when it reaches the fluke, the water is accelerated again by the fluke’s movement. This second acceleration never happens with rigid bodies. The wave along the tail, moving with increasing amplitude, creates inertial forces in the surrounding water, presumably with propulsive effect (acceleration reaction). Biological reasoning supports this inertial approach to thrust generation, as opposed to thrust by viscous effects, because the force generated by rowing appendages is approximately proportional to $u^2$. However, there is an inverse relationship between force and speed of muscle contraction, and in order to satisfy this relationship, the fast dolphin swimming speed needs a different explanation. One hypothesis is that energy is stored temporarily using the effect of added mass. Actually, fast swimming resembles what is called "push and glide" (alternating bouts of thrust and gliding). In Bluefish, which also use the thunniform swimming mode, the intracyclic changes in acceleration have been measured and were used to determine thrust and braking phases [16]. Related to energy requirements, it is obvious that "through the interaction of resistance and propulsion mechanics, the minimum power is produced" [17].

Finally, the fluke generates the main propulsive force. Pressure differences between leading and trailing sides causes water to flow around the trailing edge of the fluke, creating a vortex. During each reversal action [(P1P2) and (P3P4)], the vortex is washed away, creating a system of vortices in the wake, as shown in Figure 2. The vortices left behind by the forward moving dolphin remain essentially in place, indicating that the water is not moved backwards very much. This is interesting because backwards moving water is usually thought of as a prerequisite for thrust production.

Figure 2. Wake of a swimming dolphin with vortices and jet stream between (adapted from Fish [5])
Figure 2 shows what has been hypothesized: "a simple vortex chain is shed from the tail, which contains in its longitudinal arms the discrete vortex system and the boundary layer vorticity developed by the undulating, transverse and forward modes of motion of the swimming body" [18]. This implies that two separated vortices, drag (or side) vortex and fluke vortex, merge during phases P1 and P3. Accordingly, resistance and thrust cannot be treated separately. Furthermore, unsteady oscillatory motion seems to prevent the development of a turbulent boundary layer. Thrust is considered to be a result of a discrete vortex system which rolls up the boundary layer or shunts it into the external flow field, transferring momentum and lowering drag (see Figure 2). The change in the boundary layer with time (oscillating longitudinal shift originated by the fluke's movement) justifies the term "continuum of flow". The flow upstream of the fluke is influenced by the fluke's action, and is therefore called preformed flow.

Principles of selfpropulsion mechanics

When dolphins glide between thrust bouts, only drag is assumed to act. However, inertial effects are also acting, carrying the body forward. The drag slows down the progress, reducing the linear momentum of the system. Even when dolphins swim at cruising speed, thrust is intermittent.

Thrust forces propel the body sufficiently to accelerate the body mass and a mass of entrained fluid. Only in a towing situation at constant speed is thrust equal to body drag. For selfpropulsion, separation of forces into drag and propulsive components is not appropriate because the flapping fluke simultaneously produces a propulsive force and an "induced" drag force. The high aspect ratio of the fluke (length of trailing edge in relation to the total surface area) may lower the induced drag, but the fluke still accounts for 30% of the total drag [19].

Thrust by vortex production

As mentioned previously, the vortices left behind by the forward moving dolphin remain essentially in place, indicating that the water is not moved backwards very much. Since backwards moving water is usually thought of as a prerequisite for thrust production, how then does the dolphin transfer momentum using vortices? Liebe [20] used an experimental-numerical approach to answer this question and found that at the end of each tailbeat, water is set into rotation. He concluded "the momentum is in the core (of rotation), containing the involved mass of rotating water." According to Lighthill [11], the creation of a vortex-wake is a fundamental basis for thrust production in thunniform locomotion, since "between the vortices with altered sense of rotation a jet-like motion is induced". The momentum carried by this induced jet-like motion is related to the thrust of the animal, and gives it a high propelling efficiency, e
t

The transfer of momentum between the water set into rotation and the body has been explained differently by Aihlorn and coworkers [22]. They developed a "vortex excitation/destruction" model to explain thrust using the vortices in a different manner. In Figure 3, vortex I is excited in P1 (upstroke of the tail) during the heaving motion on the trailing side of the fluke. It is rotating clockwise. The destruction of the vortex takes place in P2 (downstroke of the tail), when the fluke starts to pitch and thus exerts a torque with a force component (in swimming direction) to stop the rotation and to propel itself forward" [22]. Simultaneously vortex II is generated on the trailing side of the fluke and is rotating counterclockwise. Vortex II creation can assist to reverse the rotation of vortex I, and gaining some energy; it is fully developed when the fluke reaches the opposite (lower) turning point. At the end of P4, vortex II is stopped. The kinetic energy of the vortex depends on the mass of water and the square of the velocity of the rotating water. During a complete cycle of upstroke and downstroke, two vortices of opposite rotational sense are produced which are canceled out during phases P2 and P4, thus creating an

Figure 3. Two phases (P1, P2) of a tail beat cycle (notice tail and fluke are out of phase); above: end position of P1 (upstroke of the tail) creating rotational momentum in a vortex (inner circle), the external half circle indicates pressure distribution of external flow field; below: end position of P2 (downstroke of the tail) stopping of vortex by applying a torque (inner circle), the external half circle indicates the beginning of another vortex; +,-: zones of positive and negative pressure.
intermittent thrust. The shorter the period of annihilation, the stronger the thrust force. A self-propelling body which leaves small or no vortices in its wake requires a smaller amount of torque (and hence, less energy) to create and cancel the rotational momentum of its vortices. Such a body has a high propelling efficiency.

Conclusion – Applications to Human Swimming

Based on steady hydrodynamical principles, a dolphin’s swimming speed, when related to muscular power, seems to be inexplicably high. Measurements and visualization of the flow along a self-propelling dolphin indicate unsteady flow conditions (cyclic changes of water displacement). Because of the unsteady motion, dolphins may experience a fluid force in reaction to the acceleration of the surrounding water. This might explain the larger thrust and/or smaller drag of a dolphin. Considering the entire flow to be a continuum, it seems likely that energy is saved by utilizing the energy in the boundary layer.

The fluke, which always lags behind the movement of the tail, flicks the preformed flow into rotation [23], generating a vortex carrying rotational momentum. Then this vortex, if annihilated by a torque exerted by the fluke, serves as a temporary storage of momentum and supports forward propulsion.

The understanding of research performed on dolphin interactive hydrodynamics as presented in this paper has some possible applications for human swimming. For example, studies of the flow around a swimmer could be performed using entrained air bubbles to show when the wake is wide or when vortices are shed by the fingertips or feet. A wide wake may indicate a high drag or reveal that too much energy was spent during the swimming motion. This information would enable coaches to give their swimmers feedback on their motor skills and technique in order to improve streamlining and to reduce the amount of wasted energy by cooperating with the water and not “fighting” with it.

The fact that all fast swimming vertebrates “prefer” oscillation of the tail and the phase coupling of heaving and pitching of the semilunate shaped fluke gives hints as to whether a swimmer is to undulate or oscillate (for example after the starts or turns). The answer is in favor of oscillation, provided the swimmer’s flexibility, especially in the ankle joints, is appropriate. Obviously, human swimmers will not be able to set water into rotation as effectively as dolphins because of the shape and inflexibility of their ankles. However, this deficit can be lowered by emphasizing the reversal action of the kick using, as much as possible, a whip-like action (phase coupling of heaving and pitching).

Finally, the effect of acceleration reaction (when there is a forward reaction of the body although no self-propelling action is noticed), was documented when analyzing the forward velocity of the center of mass of the breaststroke swimmer. The results indicated that during the recovery of both arms and legs, the forward velocity of the center of mass is less decelerated than expected as a result of a phenomena “compared with a cyclist carrying a rucksack and being pushed in the back when braking” [2]. Principally additional thrust will then occur (or less braking).

It is hoped that the progress made in the study of swimming of aquatic vertebrates will attract the interest of researchers in human swimming, and that this progress will aid their own research efforts with human swimmers.

References


Relationship between intracyclic linear body velocity fluctuations, power, and sprint breaststroke performance

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Abstract

Trained breaststroke swimmers (females, n=10; males, n=7) participated in this investigation to examine the relationship between swimming power, intracyclic linear body velocity fluctuations and sprint breaststroke performance. A velocity-video system was employed during the sprint breaststroke performance (22.86m) to measure (1) peak kick (PK) and arm pull (PA) linear body velocity, and (2) minimum linear body velocity prior to the arm pull (MVA) and kick propulsive phase (MVK). An isokinetic Cybex dynamometer was adapted to measure swimming power during a partially tethered breaststroke sprint effort. The correlation between swim power and breaststroke sprinting velocity was 0.64 (p=.11) and 0.87 (p<0.05) for males and females, respectively. The correlation between swimming power and breaststroke performance for 91.4m and 365.8m was 0.91 and 0.86, respectively (p<0.05). The male swimmers were more powerful and faster than the female swimmers (p<0.05), and covered a greater distance per stroke cycle during the sprint performance, 1.56±0.17 vs. 1.34±0.16 m.stk-1 (p<0.05), respectively. The male swimmers also obtained a greater *PK, *MVA and *PA (p<0.05), while no difference was found for MVK. The correlation between PK, PA, MVA and breaststroke sprint velocity was 0.74*, 0.91* and 0.80*, respectively (*p<0.05). This study illustrated that the ability to effectively generate power during a partially tethered sprint was an important predictor of both sprint and endurance breaststroke performance. In addition, the better breaststroke sprinters were characterized by their ability to obtain a higher peak linear body velocity during the arm pull and kick propulsive phases. Minimizing the drop in linear velocity before the propulsive phase of the arm pull was a common characteristic among the more successful breaststroke swimmers. This suggests a better streamlined body position and/or timing between the completion of the kick and start of the propulsive phase of the arm pull.

INDEX TERMS - Swimming, breaststroke skill, breaststroke efficiency, swimming power

Introduction

Many studies have illustrated that the effective application of propulsive force to the water determines, in part, a swimmer's success in competition (3,4,14,15). A major consideration in the mechanics of swimming involves reducing total body drag and the advantageous application of propulsive force by the arms and legs. Consequently, the interplay between propulsive and resistive forces (drag) becomes crucial when considering the skill level of a swimmer. The resistive forces that tend to hinder the body's motion in the water because of changes in head, trunk and limb position, results in the intermittent application of propulsive force throughout a swimming stroke cycle. Consequently, forward body horizontal velocity (linear velocity) fluctuates throughout a stroke cycle (8, 9, 15, 17).

In breaststroke, large increases in linear velocity occur during the propulsive phases of both the arm pull and leg kick (8,9). Conversely, the non-propulsive phases, arm and leg recovery, result in a decrease in linear body velocity (9). Interestingly, some breaststroke swimmers may experience a short period of positive acceleration during the recovery phase of both sets of limbs (15,16). It has been hypothesized
that the momentum from wave action created during the propulsive phase of the arm stroke is transferred to the swimmer, thereby accelerating the body forward during the recovery phase (16). Maglischo (15), however, suggests that the short period of positive acceleration is best related to a rapid movement of the arms and legs forward during the recovery phase, thereby shifting the center of mass directly forward. Regardless, it appears that the short period of acceleration is most pronounced in the more talented breaststroke swimmer.

Because less energy is wasted with a more uniform velocity, velocity variation within a stroke cycle should give an indication of movement efficiency (2,11). That is, the more even the linear body velocity, the less propulsive force which must be applied to the water to maintain a constant velocity (12,13,15). How well a swimmer moves through the water, therefore, can be assessed through the analysis of intracyclic linear body velocity fluctuations.

A simple and rapid feedback device, "velocity-video" system, has been developed which directly assesses linear body velocity fluctuations while swimming (5,8). The velocity-video system has been shown to be a valid means of measuring linear velocity fluctuations within a swimming stroke cycle (8). This system simultaneously records the swimmer's linear body velocity and swimming movement. The velocity-video system generates a real-time linear velocity-time curve superimposed on an image of the swimmer. Consequently, the coach, swimmer, and researcher can view frame-by-frame, the limb actions, body position, peak and minimum intracyclic linear velocities and intracyclic timing of the stroke. Furthermore, the curve can be divided into a propulsive and non-propulsive phase. An increase in velocity (positive acceleration) suggests that the total propulsive force is greater than the total body drag. Conversely, any decrease on the velocity-time curve (negative acceleration) suggests a period in which the total body drag is greater than the total propulsive force generated by the swimmer. Both the coach and researcher, therefore, can evaluate immediately if a swimmer is losing propulsive power during a certain phase of the stroke when the curve exhibits a large negative acceleration or less than optimal positive acceleration.

The intent of this project was to examine the relationship between intracyclic linear velocity fluctuations, swimming power during a partially tethered breaststroke effort, distance covered per stroke cycle, and sprint breaststroke performance.

Methods

Seventeen well trained college male (n=7) and female (n=10) breaststroke swimmers, who were mid-way through the regular Collegiate swim season, participated in this study. Each subject was informed of the purpose and risks associated with the research before giving written consent to participate. Percent adipose tissue was determined by using skinfold measurements. Subject characteristics are presented in Table 1.
Table 1. Subject Characteristics

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age (yr)</th>
<th>Ht. (cm)</th>
<th>Wt. (kg)</th>
<th>Percent</th>
<th>Body Fat</th>
<th>100 yd</th>
<th>200 yd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
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<td>181.9*</td>
<td>75.0*</td>
<td>11.5*</td>
<td>63.1*</td>
<td>138.8*</td>
<td></td>
</tr>
<tr>
<td>(n=7)</td>
<td>(1.5)</td>
<td>(8.2)</td>
<td>(8.0)</td>
<td>(3.0)</td>
<td>(4.0)</td>
<td>(10.4)</td>
<td></td>
</tr>
<tr>
<td>Females</td>
<td>19.1</td>
<td>166.4</td>
<td>62.8</td>
<td>22.7</td>
<td>75.9</td>
<td>165.5</td>
<td></td>
</tr>
<tr>
<td>(n=10)</td>
<td>(1.1)</td>
<td>(9.4)</td>
<td>(6.0)</td>
<td>(3.3)</td>
<td>(4.9)</td>
<td>(12.1)</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as Mean(SE).

*Significant difference between males and females, p<0.05.

**Breaststroke performance

Linear body velocity fluctuations were obtained using the velocity-video system, described previously by Costill et al. (5) and D’Acquisto et al. (8) (Fig 1.).

The system consists of a “swim-meter” (7), video camera, video recorder-monitor, a computer fitted with a Microkey video overlay system. The swim meter is composed of a non-linear elastic line passing over a low resistance reel (<70 grams resistance (5)), and over an aluminum wheel connected via a shaft to a direct current generator (Servo Tech. Hawthorne, N.J.), and to a velcro belt worn around the waist of the swimmer. During a swim trial, the swim-meter registers a voltage proportional to the instantaneous linear velocity of the swimmer. Consequently, the swim-meter measures the hip or linear body velocity of the swimmer. Maglischo et al. (14) has shown that the linear body velocity, as measured at the hip, does not differ significantly with respect to the velocity of the center of mass, suggesting the validity of the swim-meter. Costill et al. (5) has reported, however, that there are phases of the breaststroke and butterfly in which there are differences in the velocities of the hip and the center of mass. Further, Costill et al. (5) suggests that the differences are of little value from a practical standpoint to the coach and swimmer who are concerned with the movements of the arms and legs as related to forward movement of the body.

The output from the swim-meter was conditioned by frequency modulation (volt age, analog digital converter), relayed into a computer, and processed by software (Human Performance Laboratory, Ball State University) which created a graphic image of the swimmer’s linear body velocity. The velocity image was recorded and stored on the audio track of the video tape. A video image of the swim (25 yd (22.86m) breaststroke sprint) was recorded using a VHS camera strategically positioned at an underwater viewing window. The video output was relayed into a computer and processed by a Microkey overlay system (Micro-Key System, Video Associates Labs, Austin, TX). The software program superimposed the instantaneous linear velocity of the swimmer onto the video image of the swimmer, providing a velocity-time curve displayed and synchronized with the swimmers movements in the water (Figure 1). The video, therefore, allows for simultaneous viewing of body actions with the linear body velocity profile.

Velocity time curves were obtained for two “all-out” 25 yd (22.86m) breaststroke swim efforts. The swimmers were instructed to push off from the wall and go immediately into the swim. Two stroke cycles from the fastest trial were analyzed for the following variables: (1) distance covered per stroke cycle (DS, meters per stroke cycle (m/stk-1)), (2) time per stroke cycle (TS, seconds) (3) peak and minimum intracyclic linear body velocities: (a) minimum linear body velocity before the propulsive phase generated from the kick (MVK) and arm pull (MVA), (b) peak kick linear body velocity (PK), and, (c) peak arm pull linear body velocity (PA). Taking an average of the two stroke cycles provided a final value for each of the aforementioned variables.

To measure average swimming power during a breaststroke sprint, a Cybex II Isokinetic Dynamometer was adapted for use while the swimmer was partially tethered. A circular metal frame was mounted to the input shaft of the isokinetic dynamometer. The Cybex swim power unit was calibrated by dropping a variety of weights from the unit and recording the force produced. From these data a calibration curve was determined which was then used to determine force produced during the partially tethered swim power test. The swimmer wore a belt to which was attached a wire extending to and around the metal wheel. The speed of the swimmer was controlled at 0.9 m/s. Preliminary testing at our lab indicated that testing at a tethered velocity of 0.9 m/s resulted in consistent power value readings over multiple trials. The forces produced during the partially tethered swim were detected by a force transducer in the dynamometer. The voltage output from the transducer was relayed to an analog digital converter and computer where power was calculated (Software, Human Performance Laboratory, Ball State University).

Statistical Analysis

Mean, standard error, and correlation coefficients were determined using conventional statistical methods. An independent student's t-test was used for statistical comparison between males and females. Level of significance was set at the 0.05 level.

Results

A typical velocity-time curve versus changes in body configuration during one breaststroke cycle is shown in Figure 2.

One stroke cycle for linear velocity consisted of two major periods of acceleration (A1 and A2) and two periods of negative acceleration (D1 and D2). A1 was associated with the propulsive kick phase of the stroke cycle which was followed by a negative acceleration period (D1) corresponding to the completion of the arm recovery and outwep of the hands. The second acceleration period (A2) was the result of the propulsive actions of the arm pull during the insweeping phase. Once peak velocity for A2 was reached, the legs began to recover. The leg recovery consisted of flexion at the hips and knees. This resulted in an
increase in water resistance or drag reflected in a second negative acceleration phase in the stroke cycle (D2). The general pattern of intracyclic linear velocity fluctuations obtained from the velocity-video system agrees with previous reports (8,9,10,15).

Breaststroke sprinting ability varied from 1.14 to 1.66 m·s⁻¹ for the entire group. For males and females, sprinting ability ranged from 1.39 to 1.66 m·s⁻¹ and 1.14 to 1.38 m·s⁻¹, respectively. The male swimmers were faster than the female swimmers (p<0.05; Table 2). Despite no difference in time per stroke, the male swimmers were able to cover 16.4% greater distance per stroke cycle compared to the female swimmers (p<0.05, Table 2). The male swimmers were more powerful (64.45±17.63 Watts) than the female swimmers (27.33±8.64 Watts) (p<0.05). The correlation between the partially tethered swim power test and breaststroke sprint performance was 0.64 (p=.11) and 0.87 (p<0.05) for males and females, respectively. Overall, a significant correlation of 0.54 was found between swim power and DS (m·s⁻¹).

Large variations in intracyclic peak and minimum linear velocities were found: males, 0.24 to 1.87 m·s⁻¹; females, 0.23 to 1.64 m·s⁻¹ (Table 3). Despite gender, the greatest peak linear velocity was consistently generated during the kick (overall average for PK, 1.74 m·s⁻¹) followed by the arm pull (overall average for PA, 1.60 m·s⁻¹). Overall, the minimum linear velocity before the kick (MVK) and arm pull propulsive phases (MVA) was 0.23 and 1.12 m·s⁻¹, respectively. Intracyclic linear velocity measurements for PK, MVA, and PA were higher in the males compared to females by 14.0*, 14.2*, and 23.3 %*, respectively, (p<0.05), while no gender difference was found for MVK (Table 3).

Table 2. Mean (SE) values for performance time (sec), velocity (m·s⁻¹), time per stroke (TS, sec), and distance per stroke (DS, m·s⁻¹) for a 22.86 m breaststroke sprint.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Time</th>
<th>Velocity</th>
<th>TS</th>
<th>DS</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Males</td>
<td>14.98*</td>
<td>1.53*</td>
<td>1.02</td>
<td>1.56*</td>
</tr>
<tr>
<td>(n=7)</td>
<td>(1.11)</td>
<td>(0.11)</td>
<td>(0.13)</td>
<td>(0.17)</td>
</tr>
<tr>
<td>Females</td>
<td>18.25</td>
<td>1.26</td>
<td>1.07</td>
<td>1.34</td>
</tr>
<tr>
<td>(n=10)</td>
<td>(1.20)</td>
<td>(0.17)</td>
<td>(0.12)</td>
<td>(0.16)</td>
</tr>
</tbody>
</table>

Significant difference between males and females, p<0.05. Note: No underwater pull-out was allowed. Swimmers pushed from the wall and were encouraged to immediately begin breaststroke swimming once the feet left the wall.
Correlation coefficients between MVK, MVA, PK, and PA versus sprint velocity were 0.03, 0.80*, 0.74* and 0.74*, respectively, (p<0.05). PK and PA correlated with sprint power, 0.61 and 0.89, respectively (p<0.05). MVA correlated well with PK (r=0.68*), and PA (r=0.81*).

Table 3. Intracyclic linear body velocity (m/s) characteristics while breaststroke sprinting (22.86m).

<table>
<thead>
<tr>
<th>Gender</th>
<th>MVK</th>
<th>MVA</th>
<th>PK</th>
<th>PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>0.24</td>
<td>1.21*</td>
<td>1.87*</td>
<td>1.80*</td>
</tr>
<tr>
<td>(n=7)</td>
<td>(0.14)</td>
<td>(0.08)</td>
<td>(0.13)</td>
<td>(0.16)</td>
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<tr>
<td>Females</td>
<td>0.23</td>
<td>1.06</td>
<td>1.64</td>
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<td>(n=10)</td>
<td>(0.11)</td>
<td>(0.09)</td>
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</table>

Values are presented as Mean(SE).
*Significant difference between males and females, p<0.05.

Discussion and Application

A representation of a typical velocity-time curve for linear velocity during one breaststroke cycle is shown in figure 2. The tracing agrees with previous investigations of intracyclic velocity fluctuations in breaststroke (5,8,9,10,15). The drastic change in intrastroke linear velocities is due to the intermittent application of propulsive force, and the large changes in position of the arms and legs, as illustrated in figure 2. Kent and Atha (10) investigated changes in hydrodynamic resistance encountered during different phases of the breaststroke cycle at a given speed (1.5 m s⁻¹). Kent and Atha (10) found that resistance varied for the different phases of the stroke cycle in the following order: glide (9.7kg), breathing (18.5kg), recovery of legs (23.0kg), and kick (22.1kg). It is evident from these data, and the velocity-time tracing illustrated in figure 2, that the interplay between propulsive and drag forces becomes critical when considering the skill level in breaststroke swimming. For example, a negative acceleration (D1 and D2, Fig. 2) suggests that the total body drag is greater than the total propulsive forces. D1 and D2 represent recovery of the legs and arms, respectively, which results in the lowest measured linear velocities. Conversely, during the acceleration phases (A1 and A2), the total propulsive forces are greater than the total drag forces. Consequently, the highest velocities are established during A1 and A2, the kick and arm pull phase, respectively. Ideally, the propulsive forces in swimming should be applied such that a swimmer’s forward body velocity is even rather than consisting of large fluctuations, which would result in inefficient movement through the water. Therefore, the quality of movement through the water can potentially be improved by reducing hydrodynamic resistance through proper streamlining and effective application of propulsive force.

The swimmer’s ability to generate propulsive force at a given velocity (swimming power) was assessed during a partially tethered sprint effort at a set velocity. Breaststroke skill in this study was assessed, in part, by examining the peak and minimum linear body velocities generated within the breaststroke cycle. Since the average swimming velocity is related to the time required to complete a stroke cycle (TS) and distance covered per stroke (DS), we measured these variables from the velocity time curve and studied the relationship between DS, TS, minimum and maximum intrastroke linear body velocities, power, and sprint ability.

The results of this study suggested that the ability to effectively generate power is an important aspect of breaststroke sprint performance. Similar results have been reported for front crawl sprinting velocity versus power (4). This study also found that the correlation between sprint power and 100 and 400 yd breaststroke performances was 0.91 and 0.86. Collectively, these findings clearly illustrate that swimming power is an important predictor of both sprint and endurance breaststroke performance.

A swimmer’s ability to cover a greater distance per stroke cycle is related to a more effective application of force to the water, which would result in faster performance times. For example, Chengalur and Brown (3) found stroke length measurements to significantly correlate with final performance times of male and female Olympic swimmers in the 200-meter events. Those swimmers who covered a greater distance per stroke cycle were those individuals who tended to swim faster during competition. Craig and Pendergast (7) have reported similar findings. These investigators found that during competition in all swimming events, the male and female swimmers who achieved the fastest performance velocity had the longest distance per stroke. A 16.4% and 57% difference in distance per stroke and power production (p<0.05) were found between males and females (Table 2). In addition, there was a corresponding 12% difference (p<0.05) in sprinting ability between the males and females (Table 2). No gender difference in time to complete one stroke cycle was found, suggesting that stroking frequency was the same between the males and females. The male swimmer’s ability to sprint faster was therefore related to their ability to cover a greater distance per stroke cycle (1.56 vs. 1.34 m stk⁻¹).

One could conclude, therefore, that the males were able to sprint faster because they were able to generate a greater average propulsive force per stroke cycle and/or had a greater propelling efficiency (20,21). These points would account for the greater distance per stroke cycle in light of the same stroking frequency between the male and female groups. In regards to the former conclusion, the greater propulsive force per stroke cycle may be related to the male swimmers being able to recruit more available skeletal muscle mass. This seems reasonable given that the males had a greater lean body mass compared to the females (~66 kg versus ~49 kg), and
that skeletal muscle mass accounts for a good part of the body's lean tissue. Having more skeletal muscle mass to recruit during a sprint event would theoretically result in a greater absolute non-aerobic energy release and propulsive force production. This may explain the males' ability to generate a greater amount of average power per stroke cycle during the partially tethered sprint effort, and their ability to sprint faster.

In regards to propelling efficiency, one must first consider that the total swimming power generated while swimming consists of power to overcome resistance to movement (drag forces) and the power which sets water in motion (kinetic energy change of water) (20,21). Toussaint et al. (1988) and Toussaint and Beck (1992) have illustrated, in frontcrawl swimming, that the ability to minimize kinetic energy changes of water results in greater propelling efficiency. This suggests that more of the total swimming power generated can be used to overcome drag forces which would result in faster swimming.

In summary, given that the male swimmers covered a greater distance per stroke cycle compared to the females, and that stroking frequency was the same, it is possible that the males swimmers had a greater propelling efficiency. Another notion may be that there was no difference in propelling efficiency between the males and females. The difference in sprint performance may simply be a difference in the males generating a greater overall propelling force per stroke cycle. Additional research regarding propelling efficiency of breaststroke swimming is warranted, since much of this work has been done on freestyle swimming (20,21).

The faster breaststroke sprinters were characterized by their ability to generate higher peak linear body velocities during both the kick and arm pull propulsive phase. This was especially evident when comparing the males to the female swimmers. The peak velocity generated during the kick (PK) and arm pull propulsive phases (PA) were 12.3 and 18.9% greater in males compared to the females, respectively (Table 3, p<0.05). The importance of a high PK and PA was further illustrated by the correlation found between PK, PA, and sprint velocity (r=0.74) for both intracyclic linear velocity variables, p<0.05.

Another important feature of sprint success is the ability to maintain a high forward body velocity before the propulsive phase of the arm pull. For example, compared to females, the males exhibited a higher minimum velocity before the propulsive phase associated with the arm pull (MVA) (1.21±0.08 m/s vs. 1.06±0.09 m/s, p<0.05) and a faster breaststroke sprint (22.86 meters, 14.98±1.11 sec vs. 18.25±1.20 sec, p<0.05). In addition, a good correlation between MVA and sprinting velocity performance (r=0.80, p<0.05) illustrates the importance of maintaining a high MVA.

The ability to maintain a higher MVA could be attributed to better streamlining and/or timing between the completion of the propulsive phase of the kick and start of the arm pull propulsive phase. It has been suggested that the arms should make their catch almost immediately following the end of the propulsive phase of the kick (15). This timing issue is referred to as overlap timing and can be accomplished by moving the arms outward while the legs are sweeping inward during the end of the propulsive phase (15). In regards to streamlining, the trunk should be as horizontal as possible to reduce resistance to forward movement (15). By utilizing overlap timing and better body position, the period of deceleration (D1, fig 2.) can be reduced, a higher MVA established, and sprinting ability enhanced.

Obtaining a higher MVA value was found to be related to generating a higher PK velocity. The correlation between PK and MVA was 0.81, p<0.05. An important principle is that less force is needed to keep a body moving than to overcome its inertia (13). Therefore, maintaining a higher MVA contributes to reducing the inertia a swimmer has to overcome during the propulsive part of the arm pull phase. Consequently, those swimmers who maintained a high MVA tended to generate higher PA values (MVA vs. PA, r=0.81).

The ability of the swimmers to prevent a large drop in velocity before the propulsive phase of the kick was in contrast to the above findings. For example, the difference in linear velocity for males and females between PK and MVK was 1.56 and 1.23 m/s. Furthermore, a low correlation between MVK and sprint ability (r=0.03), and no difference in MVK between the male versus female swimmers suggests that MVK was not a critical intracyclic velocity discriminator of breaststroke performance. Costill et al. (5) report similar findings in that most of the better National level swimmers' velocities dropped near zero during the leg recovery phase of the breaststroke. The high drag profile, as evidenced by the great change in velocity between PA and MVK, is perhaps a result of the lower limbs assuming a position that would subsequently create the greatest propulsive force during the kick phase.

In summary, this investigation has illustrated that the ability to cover a greater distance per stroke cycle is an important feature of successful sprint breaststroke performance. The greater distance per stroke obtained by the faster swimmers suggests that they may have been able to develop a greater amount of force during the propulsive phases of the stroke cycle and therefore achieve a greater momentum in the water. A greater momentum in the water should translate to faster sprint breaststroke performance times. Coaches need to consider placing greater emphasis on enhancing distance per stroke through either increasing propulsive power and/or reducing resistance to forward movement by reducing drag during the kick, arm recovery, and arm pull phase.

It is clear that the interaction between swimming velocity, stroke length and stroking frequency is a complex one. Coaches must be careful not to enhance distance per stroke to the point of seriously reducing stroking frequency. This may actually result in a poorer performance. Furthermore, reducing the resistance to forward movement without compromising breaststroke propulsive power would
References:


The effect of depth and velocity on drag during the streamlined glide

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ABSTRACT

This study examined drag forces created when towing swimmers through water at predetermined depths and velocities. Forty experienced male swimmers of similar body shape, mass and height were towed in a prone, streamlined position through the water using a motorised winch and pulley system. A load cell was used to measure drag at the surface, 0.2, 0.4 and 0.6 m deep; and at velocities of 1.6, 1.9, 2.2, 2.5, 2.8 and 3.1 m s⁻¹. A 2-way repeated measures ANOVA revealed significantly higher drag at the surface than at 0.2, 0.4 and 0.6 m underwater for all velocities tested. For the two slowest velocities, no significant difference was found between 0.2, 0.4 and 0.6 m deep. For the velocities between 2.2 and 3.1 m s⁻¹, the drag at 0.2 m deep was significantly higher than that recorded at 0.4 and 0.6 m deep, where no significant difference was found. Results suggest that swimmers might benefit by performing their glides following a turn at 0.4 m underwater to gain maximum drag reduction, especially at velocities above 1.9 m s⁻¹. The inclusion of chest girth and a slenderness index as significant covariates, highlights the need to include these variables in analyses of passive drag.

INDEX TERMS - hydrodynamic drag, streamlining, gliding, swim turn time.

Introduction

The glide phase following a swimming turn is an integral part of swimming performance. During this phase, the two determining factors of glide performance are the initial push-off velocity and the hydrodynamic drag (resistance) acting to decelerate the swimmer. Minimising drag could produce better results than merely increasing the effort during wall push-off because it does not increase the metabolic cost. However, research has not investigated the optimal gliding depth for reducing drag. Neither has the interrelationship between drag and gliding velocities been determined conclusively.

The total resistive force experienced by a swimmer can be divided into frictional, form and wave drag. Frictional drag represents the drag produced as a result of friction between the water and the surface of a moving body, and is reported to increase linearly with an increase in swimming velocity (13). The body surface area and type of surface combine to determine the amount of frictional drag produced. Form drag is produced from a combination of eddy resistance and frontal resistance, and increases with the square of the velocity (13). This component of drag represents the degree of streamlining of the swimmer because it is directly related to the body cross-sectional area exposed to the water in the direction of travel. Wave drag occurs when swimming at, or near, the water surface when the swimmer and the movement of body segments create wave fronts (13). Wave drag is potentially the most deleterious as it varies with the cube of the swimmer’s velocity. Previous studies have demonstrated that the degree of slenderness of an object is reflected in the amount of wave drag experienced by that object (9).

Difficulties in quantifying the flow characteristics around the human body render it difficult to estimate depth/velocity effects from hydrodynamic theory. Therefore, empirical testing is required to determine the hydrodynamic drag experienced by swimmers. One method of studying drag forces in human swimming has been to tow subjects at various velocities (8, 4, 5, 7). This protocol has been used to quantify body drag in selected prone positions (passive drag) or while the subject is moving (active drag). However, the experimental designs and methodologies have limited the application of the results of these studies. With the exception of Jiskoot and Clarys (7), these studies have not analysed the drag experienced by swimmers underwater. Jiskoot and
Clarys (7) found that the passive drag experienced by swimmers at 0.6 m underwater averaged 20% higher than that recorded at the surface. This result was, in part, unexpected due to the increased contribution of wave drag to the total drag at the water surface.

Results reported by Jiskoot and Clarys (7) are not in agreement with previous fluid dynamics studies of streamlined objects, which showed that drag was greater immediately under the water surface than at a depth equivalent to a depth-to-length ratio of 0.2 to 0.4 (6, 9). An elite male swimmer of average body dimensions gliding at two chest depths (or approximately 0.4 m) underwater would therefore fall within this range (11). Underwater, the frictional and form drag components of the total drag remain fairly constant but wave drag is minimal. As the body moves closer to the surface the wave drag plays an increasing role.

Evidence regarding drag experienced by swimmers during underwater gliding remains equivocal and further clarification is required. However, given that previous studies have reported that the swim turns can comprise over one-third of the total race time in all events over 200 m and longer (14), improvements in the streamlined glide could translate to improved performance.

The purpose of this study was to examine the impact of depth and velocity on drag during a streamlined glide. Understanding the impact of depth and velocity on passive drag will provide an insight into the optimal depth for streamlined gliding after the wall push-off of a swim turn. The optimal depth will be a trade-off between the depth which offers the lowest drag force, as well as the minimal vertical distance required to resurface for stroke resumption.

**Methodology**

Forty experienced adult male swimmers acted as subjects. All were of similar body shape, mass and height to minimise the variation in drag resulting from differences in body form (3). Body mass, stature, arm span, sum of 6 skinfolds; chest, waist, hip and calf girths; and bi-acromial and anterior-posterior chest breadths were measured. All anthropometric measurements were performed according to procedures outlined by Bloomfield, Ackland and Elliott (2). The subjects were within ± 1.5 standard deviations (SD) of the mean found for elite male adult swimmers in these measures (11). A comparison between the experienced swimmers used in the current study and elite swimmers from the 1991 World swimming championships showed no significant differences between the two groups for any of the anthropometric variables (11).

In addition, three variables were selected to represent the three components of drag and used as covariates in the statistical analysis to investigate the potentially influential properties of these variables on the total drag force. Surface area was estimated using the method of Clarys (3) and used as an indication of the frictional drag. Chest girth was used to represent the swimmer’s cross-sectional area as a measure of form drag. The inverse ponderal index (height/weight$^{1/3}$) was used as a slenderness index to provide an indication of the wave drag (2). Table 1 outlines the means for the selected anthropometric variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Current Study</th>
<th>1991 World Swimming Championships</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>20.5 ± 3.1</td>
<td>21.3 ± 2.7</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>76.9 ± 6.8</td>
<td>78.4 ± 7.1</td>
</tr>
<tr>
<td>Stature (cm)</td>
<td>182.7 ± 5.6</td>
<td>183.7 ± 7.1</td>
</tr>
<tr>
<td>Arm Span (cm)</td>
<td>191.7 ± 6.5</td>
<td>192.5 ± 7.8</td>
</tr>
<tr>
<td>Chest Girth (cm)</td>
<td>101.8 ± 2.9</td>
<td>103.2 ± 4.4</td>
</tr>
<tr>
<td>Waist Girth (cm)</td>
<td>79.0 ± 3.4</td>
<td>79.4 ± 3.5</td>
</tr>
<tr>
<td>Hip Girth (cm)</td>
<td>94.3 ± 3.4</td>
<td>94.8 ± 3.6</td>
</tr>
<tr>
<td>Calf Girth (cm)</td>
<td>37.9 ± 2.2</td>
<td>37.6 ± 1.8</td>
</tr>
<tr>
<td>Bi-Acromial Breadth (cm)</td>
<td>42.1 ± 1.8</td>
<td>42.5 ± 1.3</td>
</tr>
<tr>
<td>A/P Chest Breadth (cm)</td>
<td>20.9 ± 1.3</td>
<td>21.2 ± 1.6</td>
</tr>
<tr>
<td>Sum of 6 Skinfolds (mm)</td>
<td>56.8 ± 14.5</td>
<td>60.6 ± 15.5</td>
</tr>
<tr>
<td>Body Surface Area (m²)</td>
<td>1.72 ± 0.1</td>
<td>-</td>
</tr>
<tr>
<td>Slenderness Index (cm/kg$^{1/3}$)</td>
<td>43.0 ± 1.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Mean subject characteristics and anthropometric measures from the current study (n = 40) and from the 1991 World Swimming Championships (n = 231) (11, p.22-23).

Subjects were towed along the length of a 25 m pool at four different depths (0.6 m, 0.4 m and 0.2 m underwater, and at the water surface). Figure 1 outlines the experimental set-up used during testing. At each depth, swimmers were towed for one trial at six different velocities, ranging from 1.6 to 3.1 ms$^{-1}$, in 0.3 ms$^{-1}$ increments. This velocity range covers the practical velocities experienced by club to elite level swimmers during the push-off and glide following a turn (1,10). Swimmers maintained a prone, streamlined position with hands overlapping, head between the extended arms, and feet together and planter flexed. Each swimmer was permitted practice tows at different velocities and depths to become familiar with the protocol. The depths and velocities were randomised to prevent an order effect and swimming caps were worn during trials. Water temperature was maintained at 28 °C (± 0.6 °C) to prevent variations in the coefficient of drag associated with different water temperatures (3).
Towing was performed using a 2 HP, variable control, motorised winch. Stainless steel wire was attached from the winch to the swimmer via a pulley system. The winch wound the wire around a metal drum which caused the swimmer to be towed through the water. A nylon webbing loop was connected to the end of the wire and positioned around the subject's wrist during towing. This allowed a more specific streamlined position of overlapping hands to be maintained with minimal flow disturbance from the towing apparatus.

The towing velocity was determined by using a variable control unit attached to the motor, which was adjustable to 0.1 m/s\(^1\). Pilot testing showed that this unit enabled velocity to be consistently controlled over a range of values between 1.6 and 3.1 m/s\(^1\) while towing different body types. The motor was controlled remotely via a monitoring unit which initiated towing, triggered data collection after 3 m of towing and acted as a safety cut-off by ceasing the towing 5 m prior to the pool wall (total towing distance of 15 m). A pre-loaded mechanical clutch was added to the towing system as a back up safety measure to disengage the motor in case of a failure in the electronic cut-off.

The monitoring unit also served to measure the displacement and calculate the velocity of the swimmer during towing. This was achieved using an optical sensor which detected holes drilled at equal distances at the rim of the metal drum. As the drum rotated, this sensor produced a pulse train which represented the change in displacement over a given time. A chronoscope with an embedded controller was then used to display the displacement, and calculate the instantaneous (200 samples s\(^{-1}\)) and peak velocity. When the towing wire was manually unwound over a measured 5 m distance, the error in displacement measured by the unit due to rounding errors was found to be less than 1%.

The drag forces resisting towing were recorded using a uni-axial load cell which incorporated four strain gauges mounted on a stainless steel cylinder. Calibration of the strain gauges was performed by suspending static weights from the cylinder, with results demonstrating a strong linear relationship (R = 1.00) between the load applied and the voltage recorded. The strain gauges were attached directly to a waterproof PVC capsule which contained the strain gauge amplifiers and voltage-to-frequency converter. The frequency information was transferred from the load cell capsule via electrical cable to an FM modulator transmitter. This travelled along a roller system, above water, as the swimmer was towed. The FM data signals were received on the pool deck using an FM receiver/demodulator. The signals were then passed through a frequency-to-voltage converter.
Average Glide Drag Profile

![Graph showing the average glide drag profile across different velocities and depths.](image)

Figure 2. Combined graph of average drag force for each velocity and depth (n=40).

Percentage Decrement in Drag from the Surface

![Graph showing the percentage decrement in drag from the surface at different velocities and depths.](image)

Figure 3. Percentage decrement in drag force recorded at 0.2, 0.4 & 0.6 m deep relative to the surface.

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Surface Force (N)</th>
<th>0.2 m Deep</th>
<th>0.4 m Deep</th>
<th>0.6 m Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>67.5 ± 12.0 N</td>
<td>61.1 ± 10.2 N (9.5%)</td>
<td>59.2 ± 10.3 N (12.3%)</td>
<td>58.1 ± 9.3 N (13.9%)</td>
</tr>
<tr>
<td>1.9</td>
<td>93.2 ± 12.1 N</td>
<td>86.6 ± 10.2 N (7.1%)</td>
<td>83.2 ± 10.7 N (10.7%)</td>
<td>80.4 ± 10.0 N (13.7%)</td>
</tr>
<tr>
<td>2.2</td>
<td>135.4 ± 14.6 N</td>
<td>121.8 ± 14.2 N (10.0%)</td>
<td>114.8 ± 13.0 N (15.2%)</td>
<td>109.4 ± 11.1 N (19.2%)</td>
</tr>
<tr>
<td>2.5</td>
<td>175.3 ± 17.3 N</td>
<td>153.1 ± 16.8 N (12.7%)</td>
<td>144.2 ± 15.6 N (17.7%)</td>
<td>140.5 ± 14.4 N (19.9%)</td>
</tr>
<tr>
<td>2.8</td>
<td>211.0 ± 23.1 N</td>
<td>182.9 ± 19.1 N (13.3%)</td>
<td>173.0 ± 17.0 N (18.0%)</td>
<td>169.7 ± 16.1 N (19.6%)</td>
</tr>
<tr>
<td>3.1</td>
<td>247.0 ± 25.6 N</td>
<td>216.0 ± 20.7 N (12.6%)</td>
<td>205.6 ± 21.0 N (16.8%)</td>
<td>204.1 ± 19.2 N (17.4%)</td>
</tr>
</tbody>
</table>

Table 2. Means (+ SD) for the drag force (N) at each depth and velocity along with the percentage decrement from drag recorded at the surface depth.

with the resultant voltage signals collected on a PC computer for processing using an AP30 Force Analysis Program (12) which provided for real time data acquisition and later analysis of the analogue signals.

Depth was controlled using an adjustable, two-pulley system fixed to the pool wall. The top, fixed pulley was attached to the main stainless steel tube. The lower pulley position was adjustable vertically along a track, which reached from the surface to 1.2 m deep, in 0.05 m increments. The lower pulley permitted the towing force vector to be horizontal at the required depth. An underwater camera was positioned perpendicular to the swimmer's line of motion to ensure correct depth, and the body position was streamlined and horizontal throughout the towing trial. The underwater camera was connected to a video timer and video...
recorder where the image was displayed on a monitor. Prior to the trials, calibration of the set depths was performed with each depth marked by a horizontal line on the viewing monitor.

A swimmer's depth was defined by using the mid-line of the frontal plane when the subject was in a prone streamlined position. This applied for each of the underwater depths, but not the surface depth. The surface depth was defined as the depth at which the dorsal of the swimmer's back broke the water surface and resulted in the midline being approximately 0.1 m deep for the surface towing. Towing with the midline of the body at the surface could not be achieved due to the inability of the swimmers to hydroplane across the surface at the velocities tested. During the towing trials, swimmers were provided with feedback from the video image regarding the depth level, degree of streamlining and whether a horizontal position was assumed. Any trial where the swimmer was not within +/- 0.05 m of the set depth, or was not in a horizontal streamlined position, was repeated. Swimmers were generally able to maintain the correct depth and streamlined position for each of the trials. An LED was placed underwater within the view of the underwater camera to synchronise the drag force recordings with the underwater video footage.

Data analysis consisted of a 2-way repeated measures ANOVA with the drag force as the criterion measure, and the glide depth and glide velocities as the independent variables. Body surface area, chest girth and a slenderness index were included as covariates in the analysis to represent frictional, form and wave drag, respectively. A curve analysis was initially performed on the drag data by fitting a series of standard functions to the curves in order to determine the nature of the drag-velocity trend. This analysis was performed to test whether the previously accepted exponential relationship of drag and swimming velocity was representative of the current data.

Intra-day reliability of a swimmer's drag profiles was examined by one subject performing eight trials at two different depths (0.2 & 0.6 m) and two different velocities (1.9 & 2.8 m/s) at each depth. Inter-day reliability was quantified by re-testing a subject using the standard towing protocol on two separate days.

Findings

The drag forces at each of the depths and velocities are listed in Table 2, and presented graphically in Figure 2. The percentage decrement in drag force recorded at the surface depth is also shown in Table 2 and is presented graphically in Figure 3. High intra-day reliability was indicated by coefficient of variation measures for these tests ranging from 1.1 % to 2.7 %, and a coefficient of multiple determination (R²) of 0.998. Good inter-day reliability was reflected in a strong correlation (R² = 0.89) and no significant difference (p = 0.15) was found between the testing sessions.

A curve analysis of the average drag force-velocity curves for each of the depths showed that drag followed a strong linear trend over the glide velocities tested rather than the exponential trend that was expected (13) (see Table 3).

The inclusion of the three anthropometric variables as covariates in the ANOVA revealed no changes in the significant interactions, despite the chest girth (F=24.3; p=0.000) and the slenderness index (F=9.8; p=0.002) reaching significance. The surface area covariate demonstrated no significant influence (F=0.59; p=0.441) on the outcome of the analysis.

The 2-way ANOVA revealed significant depth and velocity main effects, and depth-by-velocity interactions. Scheffe Post Hoc tests on the interactions demonstrated significantly higher drag at the surface than 0.2, 0.4 and 0.6 m underwater for all velocities. For the two slowest velocities (1.6 & 1.9 ms⁻¹), no significant differences in drag were found between the 0.2, 0.4 and 0.6 m depths. For the remainder of the velocities (2.2 - 3.1 ms⁻¹), the drag at 0.2 m deep was significantly higher than the drag recorded at the 0.4 and 0.6 m depths. The 0.4 and 0.6 m depths, however, revealed no significant differences.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Multiple R</th>
<th>F Value</th>
<th>Significance Value (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>0.999</td>
<td>1373.3</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>0.2 m Deep</td>
<td>0.999</td>
<td>3521.8</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>0.4 m Deep</td>
<td>0.999</td>
<td>2939.8</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>0.6 m Deep</td>
<td>0.998</td>
<td>1159.7</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Table 3. Results of curve analysis of the average drag force-velocity curves for each depth using a linear fit.

Discussion

Optimal glide depth has not been determined previously despite its practical significance for swimmers. Reducing the drag experienced by swimmers during the glide off the wall may reduce turn time and unnecessary energy loss. The results indicate that swimmers should perform their glides at approximately 0.4 or 0.6 m underwater to gain maximum drag reduction benefits at velocities above 1.9 ms⁻¹, or either 0.2, 0.4 or 0.6 m deep at velocities below 1.9 ms⁻¹. However, as swimmers have to resurface to resume stroking, the closer the glide depth is to the surface, the less time is wasted at stroke resumption. Thus, a trade-off exists where the optimal glide depth represents the closest depth to the surface at which there is a significant reduction in drag force. Hence, for velocities between 1.6 and 1.9 ms⁻¹, the optimal glide depth would be with the mid-line of the swimmer at 0.2 m deep.
For velocities between 1.9 and 3.1 m/s, this depth would be with the mid-line of the swimmer at 0.4 m deep.

The results of the present study differ from those of Jiskoot and Clarys (7) who found significantly higher drag forces 0.6 m underwater than at the surface. The authors suggested that the combined frictional and eddy resistance when immersing the body in the water was greater than the extra wave making resistance resulting from a partially submerged body. Given that wave drag increases with the cube of swimming velocity, its contribution to the total resistance increases as velocity increases. Hence, the low glide velocities (1.5 - 1.9 m/s) used by Jiskoot and Clarys (7) may not have been fast enough to produce a substantial wave drag. In addition, insufficient methodological details were published to determine exactly how the towing depth was defined in this study. If the swimmers were towed in a position where only a proportion of the body was submerged, then substantially lower drag forces will be recorded compared with underwater towing due to the decreased frictional and form drag. However, analysis at this depth has limited practical significance due to the inability of swimmers to hydroplane at the velocities experienced during the glide phase.

The present study recorded a higher drag at the surface depth as a result of an increased contribution of wave drag closer to the water surface. These findings concur with results obtained by Hertel (6) where a streamlined cylindrical body recorded the highest drag force just under the water surface but significantly less drag at a depth equivalent to a depth-to-length ratio of 0.2 to 0.4. This is also supported by fluid dynamic studies which demonstrate that the coefficient of drag decreases rapidly as the body increases in depth, which is a result of the decrease in wave drag (9).

The results show a 10-20% decrease in the drag force when travelling at 0.4 and 0.6 m/s relative to gliding at the surface and 7-14% reduction when gliding at 0.2 m/s. These results, although obviously significant, cannot be used directly by coaches. It would be useful to be able to relate the drag force, or percentage decrease in drag, to a practical measure of time or distance for coaches and swimmers. Hence, the time it takes to decelerate a swimmer from a push-off velocity of 3.1 m/s to a stroke resumption velocity of 1.6 m/s at the different glide depths was calculated. This deceleration time was estimated using a differential equation, based on Newton's second law, employing the drag force-velocity curves from each of the glide depths.

For the period when the swimmer has pushed off the wall and decelerates to the stroking velocity, the equation of motion for the swimmer is

\[ F_{\text{drag}} + ma = 0 \]  

(1)

where \( F_{\text{drag}} \) = total drag force, \( m \) = mass of the swimmer, and \( a \) = acceleration of swimmer.

Thus, the deceleration experienced by the swimmer is

\[ -a = -\frac{du}{dt} = \frac{F_{\text{drag}}}{m} \]  

(2)

where \( du \) = change in velocity, \( dt \) = change in time, \(-a\) = deceleration of swimmer.

The results of this study show that for each depth, drag force \( (F_{\text{drag}}) \) is linearly dependent on swimming velocity \( (u) \), i.e., \( F_{\text{drag}} = \alpha + \beta u \), where \( \alpha \) is the y-intercept and \( \beta \) is the slope of the linear equation for the average drag-velocity curve, for each depth. Therefore,

\[ -\frac{du}{dt} = \frac{\alpha}{m} + \frac{\beta u}{m} = C + Du \]  

(3)

where \( \alpha/m \) is simplified to \( C \) and \( \beta/m \) is simplified to \( D \). Rearranging equation (3) gives

\[ dt = \frac{-du}{C + Du} \]  

(4)

The deceleration time \( (\Delta t) \) can be determined by integrating equation (4) from an assumed push-off velocity \( (u_p) \) of 3.1 m/s, at time \( t_p \), to a stroking velocity \( (u_s) \) of 1.6 m/s, at time \( t_s \), i.e.,

\[ \int_{t_p}^{t_s} dt = \int_{u_p}^{u_s} \frac{-du}{C + Du} \]  

(5)

\[ \Delta t = t_s - t_p = \frac{1}{D} \left[ \ln(C + Du_s) - \ln(C + Du_p) \right] \]

Alternatively, the effect of drag at different depths can be appreciated by examining the glide distance travelled \( (d) \) in 1 s, the approximate time period for the streamlined glide after push-off. Glide distance can be calculated as follows;

\[ d = \int_0^1 u dt \quad \text{and} \quad dt = \frac{-du}{C + Du} \]

\[ \therefore \quad d = \int_{u_p}^{u_s} \frac{-udu}{C + Du} \]  

(6)

\[ \Rightarrow \quad d = \frac{1}{D^2} \left[ u_s - \frac{C}{D} \ln(C + Du_s) \right] - \left[ u_p - \frac{C}{D} \ln(C + Du_p) \right] \]

Starting at a push-off velocity \( (u_p) \) of 3.1 m/s, \( u_s \) after 1 s can be calculated using equation (5). Subsequently, glide distance can be estimated using equation (6).

Table 4 outlines the results for the theoretical deceleration glide times and the glide distance travelled in 1 s at each of the depths (see Table 4 and Figure 4). Results show an extra 0.15 s was taken to decelerate the swimmer from 3.1 to 1.6 m/s at 0.4 m underwater, than at the surface depth. This translates into an increase of approximately 0.25 m of glide.
distance by gliding at 0.4 m underwater than at the surface. Thus, the difference in the drag force between the depths is of both statistical and practical significance.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Time (s) to decelerate from 3.1 to 1.6 m/s² for each depth</th>
<th>Glide distance (m) travelled in 1 s at each depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>0.85</td>
<td>1.93</td>
</tr>
<tr>
<td>0.2 m Deep</td>
<td>0.95</td>
<td>2.12</td>
</tr>
<tr>
<td>0.4 m Deep</td>
<td>1.00</td>
<td>2.20</td>
</tr>
<tr>
<td>0.6 m Deep</td>
<td>1.03</td>
<td>2.24</td>
</tr>
</tbody>
</table>

Table 4. Calculated deceleration times and glide distances based on the drag force-velocity curves obtained in the present study.

A linear, rather than the expected exponential, relationship of the drag force-velocity curves was found over the velocity range tested. This observation was consistent for each of the glide depths. It generally has been accepted that the total drag varies exponentially with increases in velocity due to the effects of the form drag and wave drag (13). Although unexpected, this result was similar to the trends produced in previous streamlining studies (7). By extrapolating the drag force data to a zero velocity, or by investigating the drag at higher velocities than used in the previous study, an exponential relationship might be found. However, over the velocity range tested (1.6 - 3.1 m/s²), which represents the velocity range used by club level to elite level swimmers during the push-off and glide (1,10), there is a linear increase in the drag force with an increase in glide velocity.

Another important finding of the study related to the results of the covariate analysis. Although the body size range of the swimmers was limited, both chest girth, which represented the subjects’ form drag; and the slenderness index, which represented the subjects’ wave drag; significantly influenced performance. However, the body surface area, which is an indication of a subject’s frictional drag, did not influence performance, which supports the data from Clarys (3). Therefore, frictional drag could represent only a small proportion of the total drag. It is likely that, at the higher velocities, the squared relationship between form drag and velocity, and the cubed relationship between wave drag and velocity, resulted in these variables being significant. This is supported by Clarys (3) who found that the relationship between body shape and passive drag typically increases with an increase in the glide velocity. Measures representing the form drag and wave drag of swimmers need to be included in future passive drag studies.

Applications

It is important to reduce the deleterious drag experienced by the swimmer during the streamlined glide. These reductions in drag will translate directly to improved turn times. Swimmers should aim to perform their glides at a distance of 0.4 m underwater to benefit from the reduced drag forces. Closer to stroke resumption, this depth should be decreased to 0.2 m before breaking the water surface to resume stroking at race pace. Form drag and wave drag are important factors in determining the drag and thus, it is important that the swimmer holds a good streamline throughout the glide without excess body movements. An optimal gliding technique incorporates maximising the distance achieved...
from the wall push-off by minimising the deceleration rate caused by the drag force. A more efficient glide depth and streamlining will result in an increased glide distance for the same time period, thereby increasing the effectiveness of the turn. Results of this study suggest that, for experienced swimmers, a depth of 0.4 m will minimise the drag for velocities above 1.9 m/s, and a depth of 0.2 m is optimal for slower velocities.

Acknowledgments

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References

Biomechanical analysis of competitive swimming starts and spinal cord injuries

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ABSTRACT

Epidemiological data indicated that there were 25 spinal cord injuries resulting from diving from starting blocks during the years 1976 to 1984. The highest number of reported spinal cord injuries was reported in 1984 which may indicate a rising trend. The purpose of this study was to determine the effects of starting block height, as well as, the effects of starting block slope on flat and pike competitive racing dive parameters. A secondary purpose was to determine the impact forces at selected velocities. This study involved above and below water analyses. Experimental independent variables were starting block height (0.46, 0.56, 0.66, 0.76 m) and starting block slope (0, 10 degrees) as well as the type of dive (flat and pike). The result of this study indicated that any diver using a racing technique has the potential to strike the bottom of the pool with sufficient force to cause catastrophic cervical spine injury. Based on depth values alone the recommended depth of a racing pool should be greater than 1.4 m for experienced divers. In addition, starting block height, the type of dive and the starting block slope all have an influence on swimming racing depth.

INDEX TERMS - biomechanics, swimming starts, diving injuries

Prior to 1976 there were no reported spinal cord injuries resulting from competitive racing starts. However, during the years 1976 to 1984, Gabrielsen's (5) epidemiological data indicated that there were 25 spinal cord injuries resulting from competitive starting block diving. The highest number of reported spinal cord injuries reported by Gabrielsen's study was recorded in the 1980's. Pool depth, starting block height, starting block pitch and type of dive may be four mitigating factors related to competitive racing starts diving injuries. The trend for the past 20 years has been to construct competitive swimming pools with a competitive racing start diving depth of 1.2 m. In every one of the 25 starting block diving injuries reported by Gabrielsen (5) the victim made contact with the pool bottom at a depth of 1.22 m or less. Additional trends have been to increase the starting block height and to increase the starting block slope for greater speed. The pike diving technique in which the dive moves to a pike position before entry has also become popular. Although several researchers have addressed starting technique only two studies have addressed the depth of racing dives. Counsilman, et al. (2), in a study of swimming racing starts technique, stated that 88 percent of their subjects went deeper than 0.9 m and ten percent went deeper than 1.4 m. Welch and Owens (12) recommended, as a result of their descriptive data, that the minimum depth of water for starting blocks should be 1.4 m.

The purpose of this study was to determine the effects of starting block height, as well as, the effects of starting block slope on flat and pike competitive racing dive parameters. A secondary purpose was to determine the impact forces at selected velocities. The final objective of this study was to describe safe diving heights and depth based on kinematic and kinetic data.

METHODOLOGY

Subjects

Male (n=10) and female (n=10) collegiate swimmers, members of NCAA Division I swimming teams were asked to participate in this study. The subjects had a minimum of five years of competitive swimming experience and had experience in both the pike and flat racing dives. The swimmers used in this study represented a wide range of collegiate ability.
The subjects anthropometric characteristics are presented in Table 1. Body density was determined from skinfolds procedures using Lange Skinfolds calipers. Body density was calculated using the age and gender specific equation of Jackson and Pollack (7). Body surface area was calculated using the modified height-weight formula of DuBois and DuBois (4). University regulations concerning Protection of Human subjects were followed.

**Table 1. Physical characteristics of subjects.**

<table>
<thead>
<tr>
<th>gender</th>
<th>mass (kg)</th>
<th>height (m)</th>
<th>percent body fat (%)</th>
<th>body density (g/ml)</th>
<th>surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>male</td>
<td>78.5 (5.6)</td>
<td>1.82 (0.07)</td>
<td>12.9 (3.0)</td>
<td>1.07 (0.25)</td>
<td>1.85 (0.01)</td>
</tr>
<tr>
<td>female</td>
<td>64.4 (5.4)</td>
<td>1.69 (0.04)</td>
<td>22.8 (2.0)</td>
<td>1.05 (0.09)</td>
<td>1.55 (0.01)</td>
</tr>
</tbody>
</table>

**Diving Facilities**

A diving pool with a maximum depth of 4 m was utilized for this project. The facility was equipped with an underwater viewing port. A standard racing diving platform was mounted on the side of the pool. The diving blocks had adjustable mounting platforms to allow for variations in height from 0.4 to 0.8 m, and for variations in slope from 0 to 10 degrees.

**Diving Video Instrumentation**

The recording procedures involved two stationary Panasonic Digital 5000 shuttered video cameras (one above and one below the water line). The camera shutter speed was 1/1000 sec and the frame rate was 30 Hz. The above water camera was located 10 m from and perpendicular to the divers. A wide angle lens allowed the entire above water diving movement to be viewed. The under water camera was located in an underwater viewing window and perpendicular to the underwater diver. The cameras were located approximately directly over each other with one on the pool deck and the other in the underwater viewing port.

A 486 Tenex computer with a BCD Associated video playback system (Sony PVM1341 video monitor and Panasonic AG-7300 video cassette recorder) was utilized in this study. A computer program designed by Peak Performance technologies, Inc. was used to encode sequentially every field of the tape. When a field was played back on the playback system, the computer was able to detect the frame numbers currently being played; thus time between any two given fields was determined with an accuracy of 1/60 of a second.

To facilitate the location of segmental endpoints during the video analysis, flashlight bulbs (0.6 watt) connected to two 1.5 v batteries were taped to the top of the head, shoulder, elbow, wrist, hip, knee and ankles of each subject's right side. The illumination of the body parts was necessary to ensure acceptable digitizing locations of segment end points during bubble-plagued underwater entry. Above and below water photographic background fields included background identification markers, subject number, trial experimental condition and date of testing.

**Procedures**

The subjects were asked to attend three testing sessions with at least 24 hours between sessions. The first session for all subjects included anthropometric determinations and familiarization with the experimental procedures. The next two sessions involved one session for the pike dive and the other for the flat dive.

Each data collection session required each subject to perform a maximum of twenty dives (three dives from each of the following heights 0.46, 0.56, 0.66, and 0.76 m above the water line with 0 degree starting block slope, and three dives from 0.46 and 0.76 m above the water line with a 10 degree starting block slope). The type of dive was randomized between subjects.

**Data Analysis**

Every video field from five fields before take off to total body water entry were digitized in the above water video data. Every video field from water entry to either change in direction or obvious swimming control (i.e., arm and leg swimming movement) of underwater movements was digitized from the under water film data. The location of the center of gravity were computed by use of the inertial data of Clauser, McConville, and Young (3) To minimize digitizing error, a data smoothing computer procedure (Butterworth digital filter) was applied to the displacement data prior to calculating velocity and acceleration.

Factorial analysis of variance statistical procedures was used to determine differences between the main effects of height, slope and type of dive. The alpha level of significance was set at 0.05.

**Kinetic Analysis**

In order to estimate impact force, a device that resembled a pogo stick was designed and instrumented with an Omega Engineering Strain Gauge (6/1201g3) and interfaced to a 486 Tenex computer. The device was calibrated prior to testing. The device was strapped onto one leg of an athlete (mass = 81.6 kg, height = 1.75 m) which stepped into the pool from four different heights above the water level (i.e., 0.0, 0.8, 1.4 and 1.8 meters). Ten impacts from each height were recorded. The different heights were used to induce differing descending and impact velocities. The underwater trajectory of the subject and the device were videotaped.
Table 2. Pike and flat dive at the selected heights mean and standard error values for the center of gravity at water entry.

<table>
<thead>
<tr>
<th></th>
<th>Pike</th>
<th></th>
<th>Pike</th>
<th></th>
<th>Flat</th>
<th></th>
<th>Flat</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.46</td>
<td>0.56</td>
<td>0.66</td>
<td></td>
<td>0.46</td>
<td>0.56</td>
<td>0.66</td>
<td>0.76</td>
</tr>
<tr>
<td>Angle</td>
<td>-38.8</td>
<td>-40.8</td>
<td>-42.8</td>
<td>-43.0</td>
<td>-37.6</td>
<td>-39.7</td>
<td>-41.2</td>
<td>-42.2</td>
</tr>
<tr>
<td>(deg)</td>
<td>0.7*</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Horizontal Displacement (m)</td>
<td>3.01</td>
<td>3.07</td>
<td>3.14</td>
<td>3.21</td>
<td>3.04</td>
<td>3.12</td>
<td>3.21</td>
<td>3.29</td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.06</td>
<td>0.09</td>
<td>0.08</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Horizontal Velocity (ms⁻¹)</td>
<td>3.8</td>
<td>3.8</td>
<td>3.7</td>
<td>3.8</td>
<td>4.0</td>
<td>3.9</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Vertical Velocity (ms⁻¹)</td>
<td>-3.0</td>
<td>-3.3</td>
<td>-3.5</td>
<td>-3.6</td>
<td>-3.1</td>
<td>-3.3</td>
<td>-3.6</td>
<td>-3.7</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Resultant Velocity (ms⁻¹)</td>
<td>4.9</td>
<td>5.0</td>
<td>5.1</td>
<td>5.2</td>
<td>5.1</td>
<td>5.1</td>
<td>5.4</td>
<td>5.5</td>
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<tr>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* lower value is standard deviation

RESULTS

**Entry Center of Gravity Displacement**

The horizontal displacement of the center of gravity at water entry mean and standard error values are found in Tables 2. There was a significant main effect (p < .01) for the variable for height. As height increased from 0.46 m to 0.76 m, the horizontal displacement of the center of gravity increased. Each increment of height resulted in an 0.07 m increase in horizontal displacement. There was no significant slope or type of dive effect on the entry horizontal displacement of the center of gravity.

**Entry Center of Gravity Angle**

The angles measured were determined from horizontal and vertical velocity values. The entry angle mean values for the pike dive ranged from 38 (±3.3) to 44 (±4.0) degrees with an increase in number of degrees with each height. The flat dive entry angles ranged from 37 (±3.3) to 41 (±2.7) degrees. No significant main effect was indicated for type of dive, slope or height.

**Entry Center of Gravity Velocity**

The velocity of the center of gravity upon water entry was analyzed in terms of the horizontal (x), vertical (y) and resultant components. The mean and standard error values for each aspect of the center of gravity velocity are presented in Tables 2. The main effect of height had a statically significant influence on the vertical (p < .01) and resultant velocity (p < .01) mean values. As height increased, the vertical and resultant velocity values increased. A significant slope effect was noted in both the flat and pike dives. As the angle increased from 0 to 10 degrees, there was a corresponding increase in the vertical and resultant velocity values. The average increase in velocity due to slope was 0.19 ms⁻¹. The effects of type of dive had no significant effect on the velocity of the dives. Table 2.

**Underwater Center of Gravity Displacement**

When the head reached maximal depth, the center of gravity was continuing to move in a downward direction. At the head's lowest trajectory point, the center of gravity's displacement and velocity were determined. Vertical displacement statistical analysis (ANOVA) indicated no significant difference between the two type of dives for the depth, and a significant difference (p < .00) in the depth of the center of gravity due to height (Figure 1). As height increased there was significant increases in the depth of the dive. The differences in center of gravity vertical displacement due to height were somewhat higher for the pike dives than the flat dives. Therefore, the effects of height on center of gravity
vertical displacement appears to influence the pike dive more than the flat dive. In addition, starting block slope had a significant effect (p < .01) on the depth of the dives. The depth of the dives increased approximately 0.1 m/s² with an increase in starting block slope.

Center of gravity horizontal displacement ANOVA indicated that of the three main effects (height, type and slope) only height had reached a level of significance (p<.00). There was a significant 0.2 m increase in horizontal displacement with an increase in height. Starting block slope appeared to have little effect on the horizontal displacement of the center of gravity. The displacement mean values ranged from 3.6 to 4.1 m.

Center of Gravity Velocity.

The center of gravity's resultant velocity at the maximal depth of the head and the two components of resultant velocity (horizontal and vertical components) were subjected to statistical analysis. Figure 2 presents the mean velocity values for each independent height variable. None of the three main effects or the interactions for the velocity of the center of gravity were significant.

Angle of Head, Trunk and Center of Gravity

At the lowest point of the dive there was no significant main effect on either the head, trunk or the center of gravity angle relative to the horizontal. The pike dive center of gravity angle ranged from -19.2 (±3.4) to -22.7 (±3.2) degrees. The flat dive center of gravity angle ranged from -17.1 (±4.1) to -19.8 (±3.6) degrees. The angle increase with the height of the diving blocks. The angle of attack at the lowest point of the dive was calculated from the angle of the trunk relative to the horizontal and the center of gravity angle. Pike head angle values ranged from 1.9 (± 2.1) to 5.5 (± 5.4) degrees above the midline of the body. In contrast the flat dive head angles at the ranged from -0.7 (±3.4) below the midline of the body to 1.9 (± 3.2) above the body's midline. The data describing the angle of attack is presented in Figure 3. There were no significant main effects.
**Head Depth**

Figure 4 presents the mean and standard error values for the head depth at the lowest point in the dive. Statistical analysis indicated that the type of dive ($p < .026$) and the height of the dive ($p < .00$) were related to a significant effect. The pike dive mean values were significantly deeper than the flat dives, and as the height of each dive increased, the vertical displacement of the head increased. The interactions were not statistically significant.

**Impact Device**

The subject and the attached impact force device struck the pool bottom with peak impact forces ranging from 488.39 N to 13,604.51 N. The duration of the impacts ranged from 0.09 to 0.23 seconds. Maximum impact velocity, derived from video data, ranged from 0.16 to 1.6 m s$^{-1}$. Using the impact force and impact velocity data, a regression equation was employed to describe the relationship. The regression equation $R$ value was 0.85. The regression equation is as follows:

$$\text{Force (N)} = 2215.2 + 3900.3 \text{ velocity}$$

**Discussion**

The results of this study indicated that starting block height, slope and type of dive, individually or in combination, had a significant effect on the depth of the dive. As starting block height and slope increased, there were significant increases in depth of either the center of gravity or the head. An increase in depth of the dive could result in injury. Therefore, to reduce the potential for diving injuries, starting block height, and slope as well as type of dive should be considered.

The above water data may be of interest to the coach, but the results of this study noted that above water velocity is only a weak indicator of under water depths and velocities.
The correlation between entry velocity and velocity at the lowest point was $r = 0.22$. The lack of relationship between entry and maximum depth velocity can be explained by drag and lift forces. During a headfirst entry in the water, the body encounters a pressure or drag force which opposes the entry. Drag is influenced by maximal body cross-section as well as body height. In addition to drag, the diver entering the water headfirst begins to develop lift forces as soon as the hands enter the water and begin to plane against the resistance of the water. The lift forces can be generated to steer the head and body in any direction that is desired. The diver who fails to generate sufficient lift force is probably the diver at risk of impact with the pool bottom. The data presented here indicated that the diver that deviates from the mean by more than two standard deviations may contact the 1.4 m pool bottom. In the worst case the velocity could be high enough to cause injury.

The ultimate goal of this study was to determine the critical depth of a racing pool that would prevent catastrophic cervical spine injuries resulting from a racing dive. The final analysis of potential diving injuries leading to paraplegia or quadriplegia is related to the force of impact. The critical impact force identified to cause rupture of the cervical discs or fracture of the cervical vertebral bodies has been estimated to be between $3,924-7,840$ N (400-800 kg f) by Torg (11) and 1,254 to 5,017 N by Stone and States (10). A contact speed of 0.91 ms$^{-1}$ was identified by Stone and States (10) to be in excess of the required force to rupture the cervical discs or to fracture cervical vertebrae. Based on the force velocity regression equation presented in our study a force of 5764 N was associated with a velocity of 0.91 ms$^{-1}$, and all of the dives presented here were in excess of the 0.91 ms$^{-1}$ value. Therefore, if any of the divers, in the present study struck the
top of their head with the pool bottom at a vertical velocity equal to or even slower than the actual values reported, injury to the cervical vertebrae could occur.

The above speculation were based on the assumption of vertical compression impacts. Allen, et al. (1), Kewalramani and Taylor (8), Gehweiler, et al. (6) have described hyperextension and hyperflexion as the two dominant head positions related to cervical spine lesions and cord damage. The study of a combination of tension, compression and torsion in cervical spine movements requires the determination of moments. Shea, et al. (9) reported a 7 Nm mean moment for failure of C2-C5 vertebrae with flexion rotation of less than 33 degrees and 12.1 Nm mean moment for failure of the lower cervical vertebrae.

Data in terms of moments would require knowledge of head angle, the point of impact and the distance from impact to axis of rotation. The angle of the head relative to the pool bottom was quite variable in the data presented here. The head angle for the pike dives were generally a few degrees above the horizontal. With an angle above the horizontal the chin would be the most likely contact point. The flat dive head angles were generally a few degrees below the horizontal; this position would necessitate a forehead contact position. Assuming that the perpendicular distance between the cervical vertebrae axis of rotation and the chin or forehead is approximately 0.04 m; a 0.04 m moment arm would require a force of 175 N to produce a moment of 7 Nm and 302.5 N would be needed to produce 12.1 Nm moment. Our velocity (based on regression equation) values associated with a 175 or 302 N force would be lower than 0.01 ms⁻¹.

Other considerations that may influence diving pool impacts are impact duration and slippage. The amount of
force absorbed either by the pool bottom or by the head and neck are factors that could possibly reduce the magnitude of the impact force. The nature of the pool bottom, usually tile or concrete, provides little absorption or force; however, impact not directed through the head’s vertex would allow for some absorption of force.

Torg (11) presented an estimate of the impact forces related to football collisions resulting in paraplegia or quadriplegia. Based on the law of conservation of momentum, Torg (11) estimated the forces leading to cervical spine trauma. The data presented by Torg assumed an 0.06 second impact. The basis for the duration assumption was not defined. We calculated the time needed to rotate the head from 70 to 95 degrees at impact velocities ranging from 2.0 to 4.0 m/s. The calculated rotation time (duration) values necessary to rotate the head ranged from 0.032 to 0.012 seconds (using the 2.0 to 4.0 m/s velocity values). Using the impulse momentum relationship (Ft = m(v1 - v2)) with an impact velocity of 2 m/s for a duration of 0.0332 seconds, a 70 kg swimmer would generate a 4375 N force which is force large enough to cause cervical spine injury.

In conclusion, the results of this study indicate that any diver using a racing technique has the potential to strike the bottom of the pool with sufficient force to cause catastrophic cervical spine injury. The fact that none of the experienced divers in the present study ascended to a depth greater than 1.4 m may point out the value of good technique. The hazard may not be so great for the experienced diver as for the inexperienced diver or for the diver who is not concentrating on the proper technique while diving. Based on depth values alone, the recommended depth of racing diving pool should be greater than 1.4 m for experienced divers. In addition, starting block height, the type of dive and starting block slope all have some influence on racing dive depth. Therefore, a reduction in starting block height, a flat dive and zero starting block pitch could aid in reducing the depth of the racing dives.

References

Optimal taper period in female swimmers

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Abstract

Despite the widespread use of tapering, there are few empirically-based guidelines for determining appropriate taper length. Fifteen, well-conditioned female collegiate swimmers (five each of sprinters, middle distance, and long distance) were studied during a four week end-of-season taper (EST) to identify the optimal period of decreased training load by monitoring changes in blood-lactate concentration and performance times derived from a test work set (4 x 100 yards @ 1:30 minute intervals at 80% of maximum heart rate). Statistical analysis indicated no significant differences between the groups at baseline for performance or lactate values, nor across the EST for performance or lactate. Therefore, the data were collapsed across groups and a significant multivariate effect for time ($F(8,7)=0.12, p<0.01$) revealed significant trends in both sets of data with inflection points occurring at the end of the second week/beginning of the third week of EST. Performance times and lactate values, which had been decreasing, began to increase back toward starting values. The findings suggest that a taper of approximately two weeks may be the limit of recovery and compensation time before detraining is evident and, therefore, preferable to the commonly utilized four week EST.

INDEX TERMS - taper, lactate.

Introduction

Although considerable research has been conducted on general training methods and biomechanical analysis to improve swimming performance (17), most swimming studies have focused on determining the best training intensity and pace to prepare for competition (6). Very little work has been done on the physiological effects of tapering, arguably the most widespread pre-competition training strategy used in swimming, and, consequently, there seems to be no phase of training about which coaches are less certain. Based on anecdotal evidence, coaches rely on instinct to evaluate the intensity and length of the end of season taper (EST) and consequently recommendations vary.

Taper is frequently described as a stage of "overcompensation" or rather physiological "supercompensation," (17, 21) and is based on the observation that, after a period of high-intensity/high-volume training, maximal performance may be enhanced by rest. A reduction in training (21), seemingly allows the body to complete its adaptive responses to training overload. Although insufficient research has been done to allow calculation of the duration of the optimal taper period, indications are that effective taper should entail a reduction in training volume with a preservation of training intensity (3).

One of the tools commonly used to evaluate the effectiveness of physical training is the measurement of blood-lactate concentration. The amount of lactate present in the blood at any given time is related to both the production rate of lactic acid in the working muscle, as well as the rate of blood-lactate clearance by the liver, heart, skeletal muscles, etc.

In most swimming events, the main source of energy is glycolysis, an anaerobic process that results in the production of pyruvate inside the cytosol of the muscle cell. This process is controlled by several factors such as $[Ca^{++}]$, $[H^+]$, $[ADP]$, and $[Pi]$. When the rate of ATP hydrolysis is high, the glycolytic pathway accelerates, and the rate of pyruvate production is elevated. Accumulation of pyruvate can deem the process thermodynamically unfavorable, and glycolysis is halted. Under most conditions, pyruvate is converted to acetyl-CoA and directed to the aerobic energy systems (Krebs Cycle and electron transport chain), where it is broken down
to CO₂ and H₂O, while simultaneously producing ATP for continued muscle activity.

The elevated cytosolic NADH+/NAD ratio that accompanies rapid pyruvate production, favors the conversion of pyruvate to lactic acid. By forming lactic acid, NADH+ is converted to NAD, a necessary cofactor in the glycolytic pathway. Lactate is consequently removed from the working muscle by adjacent consumption by non-working muscle fibers and/or by diffusion into the blood. Lactic acid therefore, is not a waste product, per se, but rather a necessary metabolite that allows continued energy production via glycolysis. Lactic acid is a strong acid (pKa = 3.19) and thus, it is rapidly oxidized to its salt form called lactate with simultaneous increase in intracellular [H+]. It may be the increase in [H+] disassociated from lactic acid that ultimately limits intensive, short-duration muscular activity.

During high-intensity exercise, both blood-lactate concentration and intramuscular [H+] have been shown to increase (25). The decreased pH has been shown to significantly contribute to the development of muscle fatigue (20). Thus the inability of the muscle to sustain the desired work output can be at least partially linked to decreased intramuscular pH. Since it is methodologically impossible to monitor intramuscular pH levels, the simultaneous changes in blood lactate are measured instead. It has been proposed that as the intensity of exercise increases, so does the blood-lactate concentration, mainly due to increased glycolysis and an upper limit to the removal of lactate by other tissues (22).

For a more complete description of the above mechanism, the reader is directed to the excellent monograph by A. Weltman (24).

Changes in lactate values for a given absolute workload can be indicative of the fitness level of an athlete. An increase in aerobic capacity (VO₂max), as well as blood shunting, increased capillarization around working muscle fibers, greater aerobic enzyme concentrations and increases in the size and number of mitochondria, all contribute to the reduction of blood-lactate concentration at a given intensity. The amount of lactic acid produced depends on the intensity of work, the duration of the work and the muscle mass involved. Low pH (that is, more acidic environment) is associated with decreased environments force production and work rate. Thus, it has been suggested that lower blood-lactate profiles can be explained, in part, by an increased rate of maximal oxygen consumption, (VO₂) reflective of a higher aerobic capacity, and a simultaneous increase in the ability to consume lactate at a given submaximal workload (23).

From the previous discussion it is clear that the relationship between blood-lactate concentration and swimming velocity exists (5). Lactate levels during recovery from maximal and submaximal effort (as indicators of training intensity and functional status of swimmers) (2, 6, 15) have been of ongoing interest to swim researchers. Most recently, Pelayo et al. (19) investigated blood-lactate concentration changes during training and performance over 23 weeks as a means to identify variations attributable to swimming at maximal intensity during an entire season of training. However, to this point attempts to use lactate levels to identify functional changes during the taper have failed to yield significant results (14). The purpose of this study was, therefore, to monitor changes in blood-lactate concentration and performance during a four-week EST as a first step in identifying the optimal recovery and adaptation period of a taper.

Methodology

Participants

Fifteen competitive collegiate female swimmers ranging in age from 18 to 21 years (M ± SD: 19.8 ± 0.77 years) with maximal oxygen consumption values ranging from 41.78 to 59.57 mlO₂·kg⁻¹·min⁻¹ (M = 48.50 ± SD 5.18) volunteered to participate in the study. Treadmill running (Balke protocol) was used to determine values for VO₂max. The participants were divided into three groups based on daily training yardage. The sprinters swam between 5800 and 6200 yds daily for the season, the middle distance group between 6200 and 7200 yds, and the long distance group between 7200 and 8200 yds.

Protocol

Training

The EST (end-of-the-season taper) consisted of a 25% reduction in training yardage per week for four weeks. As a daily average, pre-taper training consisted of 6800 yds. The warm-up consisted of 10 minutes of stretching and a total of 1000 yds (300 yd swim, 200 yds pull, 200 yds kick, and 300 yd swim). The warm-down consisted of an easy 300 yds swim followed by 10 minutes of stretching. The total for the warm-up and warm-down was 1300 yds and it remained the same for the entire taper period.

The average daily training yardage minus the warm-up and warm-down was 5500 yds. This amount (training yardage) was reduced by 25% by the end of each week, from the end of the previous week. By the end of week 1, the average training yardage was reduced to 4125 yds, by the end of week 2 it was down to 3100 yds, by the end of week 3 it was down to 2300 yds, and the end of week 4 it was 1750 yds. Total training distance for each day consisted of 10% race pace and 5% sprint assisted. Both of these percentages remained the same for the entire taper. As for the other two components of the training yardage, the component at threshold level was 65% of the total training yardage at the end of week 1, and was reduced by 15% each week throughout the taper. At the end of week 2, the amount was reduced to 50%, week 3 was reduced to 35% and week 4 was reduced to 20%. The
aerobic component of the training yardage (light kicking and drills) increased over the taper period. The percentage increased from 20% of the training yardage at the end of week 1 to 35% at the end of week 2, 50% at the end of week 3 and 65% at the end of week 4.

Measurements

Swim performance and blood-lactate values were obtained one week prior to the beginning of the EST (baseline) and twice a week through the EST (experimental) for a total of nine recording times. The work set consisted of four 100-yard swims at intensity corresponding to 80% of maximum heart rate (Hrmmax) with a swim beginning every minute and thirty seconds (1). The intensity of the test set was set at 80% to reflect regular training intensity. Participants monitored their heart rate by palpation of the radial artery for 6 seconds immediately upon completing each 100-yard swim. This technique is used extensively in swimming workouts, and all advanced swimmers are very proficient and accurate in measuring their heart rate. Should there be error associated with this measurement, this error is believed to be consistent through practice and testing, thus, the results of this testing protocol are not particularly affected. Sets during which the heart rate was higher or lower than the prescribed intensity were repeated. It was hypothesized that, if differences exist in rate of removal of lactate from the muscle these differences would exist between groups and not within. There was a five-minute rest between the completion of the warm-up and the beginning of the test set (16).

For analysis, the average time of the four 100 yard swims in each test set for each participant was used as raw data to monitor changes in performance. Lactate levels, in millimoles per liter (mM/L), were obtained from blood samples taken within one minute following completion of the test set via a finger stick using an Autocl, collected in a capillary tube and analyzed by a Yellow Springs Instruments lactate analyzer (model #2700).

Data Analysis

One-way analysis of variance was employed to examine differences in both performance and lactate scores at baseline. Due to the small participant-to-variable ratio, the analysis of doubly multivariate repeated measures was not performed on the dependent variables of performance and lactate. Instead, a mixed model multivariate analysis of variance (MANOVA) with Group as the between-subjects variable, Time as the within-subjects variable, and scores of either performance or lactate across the nine assessments as a dependent variable were used to assess changes in performance and lactate scores. Follow-up univariate analysis was conducted on significant MANOVA.

Results

Performance

The one-way ANOVA indicated no group differences in baseline measures, \( F(2,12)=1.63, p=0.24 \), indicating the scores on performance were homogeneous for the participants in the three groups at the beginning of the taper period. Similarly, there were no difference in lactate levels measured during the baseline test for the three groups [one-way ANOVA, \( F(2,12)=2.00, p=0.18 \)] or between Group and Time \( [F(16,10)=0.17, p=0.61] \). Based on these findings, data were collapsed across groups and a within-subjects analysis of variance was performed.

There was a significant multivariate effect for Time \( [F(8,7)=0.12, p<0.01] \) which was followed up with univariate analysis. Results indicated significant linear \( [F(1,14)=14.40, p=0.002] \) and quadratic \( [F(1,14)=23.81, p<0.0001] \) effects. The results of the trend analysis are in Table 1.

Table 1. Trend Analysis of Performance Data

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
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<td>.006</td>
<td>1</td>
<td>.006</td>
<td>14.40</td>
<td>.002</td>
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<tr>
<td>Quadratic</td>
<td>.010</td>
<td>1</td>
<td>.011</td>
<td>23.81</td>
<td>.0001</td>
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<tr>
<td>Total</td>
<td>.018</td>
<td></td>
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</tbody>
</table>

Although both linear and quadratic trends were significant, the quadratic SS of 0.01 accounted for \( 0.01/0.018 \times 100 = 56\% \) of the variability in performance. The value of 0.018 is the overall SS involving various degrees of the polynomial (e.g., linear, quadratic, cubic, quartic, etc.) in the regression equation. The linear SS of 0.006 accounted for 0.006/0.018 \( \times 100 = 33\% \) of the variability.

Individual parameter estimates indicated a significant negative linear trend, \( \bar{S}=0.021, p<0.002 \), coupled with a positive quadratic trend, \( \bar{S}=0.026, p<0.001 \). Figure 1 presents a plot of mean scores on performance against the assessments made over the four week period. The mean scores showed a linear decrease from baseline to the end of Week 2 and then a gradual upward trend at the beginning of Week 3.

Lactate

The one-way analysis of variance showed no group differences in lactate levels taken at baseline, \( F(2,12)=2.58, p = .12 \). Similar to the analysis on performance, the multivariate effect for Group \( [F(2,12)=3.60, p > .06] \) and the interaction between Group and Time were nonsignificant \( [F(16,10)=17, p = .74] \). As a result, data were pooled across the groups and a within-subject analysis of variance was then performed.
Figure 1. **Performance score trend**

![Graph showing performance score trend](image)

**Assessment points**

Figure 1. Trend in performance times (mean of x swimmer or swimmers +/-)

Multivariate test showed a significant Time effect \[ F(8,7) = .12, p < .01 \] and follow-up univariate analysis indicated significant linear \[ F(1,14) = 55.88, p < .0001 \], quadratic \[ F(1,14) = 468.81, p < .0001 \] and quartic \[ F(1,14) = 95.07, p < .0001 \] effects. The results of these significant trend components are shown in Table 2.

**Table 2. Trend Analysis of Lactate Data**

<table>
<thead>
<tr>
<th>Source</th>
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<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
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</thead>
<tbody>
<tr>
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<td>142.09</td>
<td>1</td>
<td>142.09</td>
<td>55.88</td>
<td>.0001</td>
</tr>
<tr>
<td>Quadratic</td>
<td>174.96</td>
<td>1</td>
<td>174.96</td>
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<td>.0001</td>
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<tr>
<td>Quartic</td>
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<td>8.59</td>
<td>95.07</td>
<td>.0001</td>
</tr>
<tr>
<td>Total source</td>
<td>332.08</td>
<td></td>
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<td></td>
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</tbody>
</table>

Inspection of variance accounted for by each of these trend components indicated that approximately 43% \( (142.09 / 332.08 = .43) \) of variability in lactate level was accounted for by the linear component, 53% \( (174.96 / 332.08 = .53) \) by the quadratic component, and only 3% \( (8.59 / 332.08 = .03) \) by the quartic component.

Parameter estimates associated with each of these significant trends (linear, quadratic, and quartic) indicated a negative linear slope, \( \bar{s} = -3.08, p < .0001 \), coupled with a positive quadratic trend, \( \bar{s} = 3.42, p < .0001 \). Figure 2 presents a plot of mean lactate values across the EST and shows the same trend as that found in the performance data; the mean scores displayed a steady decrease from the baseline to the measures taken between the end of Week 2 and the beginning of Week 3. A significant upward trend occurred between the first assessment in Week 3 and second assessment in Week 3, \( \bar{s} = -3.09, p < .01 \).

**Discussion**

The use of lactate concentration to monitor training intensity and fitness levels in swimmers has been a common practice for some time. It is clear that continued activity at a high level will result in an accumulation of lactate linked to an inevitable drop in activity intensity. As the concomitant decrease in intramuscular pH has been shown to adversely affect the activity of key enzymes of glycolysis.

One of the goals of repeated exposure to aerobic loading, is for the body to undergo several physiological adaptations so that one can continue working at a higher intensity. Additionally, repeated aerobic overload improves the performance of the lactate removal mechanism, a fact that has been emphasized in a number of studies in animals and humans. For example, Brooks and Gaesser (4) and Fukuba et
al. (12) found evidence for an improved rate of metabolic blood-lactate clearance resulting from physical training in human subjects. Donovan and associates (10, 11), in a series of studies using exogenous lactate infused into endurance-trained rats, also demonstrated an increased capacity to improve regulation of blood-lactate concentration through more efficient lactate removal.

The performance consequences of these adaptations can be seen in two ways: a) a given lactate concentration, will occur at a greater work load, and b) at a given work load, an athlete will have a lower lactate concentration. The presumed advantage of these metabolic adaptations is that the athlete can sustain a greater workload before decrements in performance are evident.

Unfortunately, these adaptations are prevalent only as long as high habitual loads are placed on the working muscles. Although the empirical evidence guiding the process of taper require a decrease in workload to facilitate performance, if the period or magnitude of the load reduction is too extensive, aerobic metabolism will regress to a lower level. Thus, detraining may be an inevitable consequence of poorly timed or badly administered EST.

Costill and co-workers (7, 8) showed that cessation of training resulted in a rapid decline in the respiratory capacity of muscles over a four-week period. Similarly, other studies have shown marked decreases in the levels of mitochondrial enzymes responsible for aerobic energy following varying period of reduced work, resulting in the loss of the positive adaptations that accrued during a long season of high intensity training (9, 13, 18). One finding of this exploratory study was that performance was improved at the end of the two-week taper period and the four-week taper period, compared to the normal training. However, the common practice of a four-week taper may be counterproductive with regard to the removal mechanism, when compared to the two-week taper. The blood-lactate values measured in the second half of the EST period as well as the performance times may be indicative of a reversal of the improvements that followed the initial reduction in training load, in essence a "detraining" effect. From the available data it is not possible to determine whether the increased lactate for the same exercise intensity is a result of detraining and if so whether detraining was due to the extended period of reduced load, too extensive a decrease in load (below 50% of normal yardage after the second week), or a combination of the two. The relative...
contribution of these factors to detraining in EST needs to be examined in future research on taper.

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Note

In order to narrow the focus of the In-Print bibliography, we have eliminated some articles that do not contain a significant scientific or research emphasis. This includes the entire Administration, Biography, Facilities, and Sports Law sections plus several articles from the Coaching, General, and Teaching sections. Readers who have a special interest in these areas may obtain a complete listing from the editor of the JSR.

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WOMEN


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"Effect of depth and velocity on drag during the streamlined glide"
1. Swimmers should perform their streamlined glide at _____ deep immediately after pushing off the wall.
2. The _______ depth produced significantly higher drag than the remainder of the depths for each velocity.
3. The increase in drag force at the surface is due to an increase in the _______ component of total drag.

"Relationship between intracyclic linear body velocity fluctuations, power, and sprint breaststroke performance"
1. The breaststroke cycle is marked with two major periods of ___________ (positive acceleration) and two major periods of ___________.
2. Specific key discriminating factors between a faster and slower breaststroke swimmer and between males and females include: _____________________________.
3. Theoretically, enhancing breaststroke skill can be accomplished by _________________.

"Biomechanical analysis of competitive swimming starts and spinal cord injuries"
1. The three above-water factors which influence the depth of a competitive-racing dive are: ___________, ___________, and ___________.
2. The recommended competitive-racing pool depth is ___________.
3. The diver who fails to generate a sufficient underwater ___________ is a diver at risk to impact the pool bottom.

"Optimal taper period in female swimmers"
1. Lactic acid allows conversion of _______ to _______, which is a necessary cofactor in glycolysis. The metabolic fate of lactic acid is generally ___________ via the Krebs Cycle and thus lactic acid can be seen as an important energy source for muscles.
2. Lactic acid is an organic _______ and when a_____ is disassociated from lactic acid the pH of the tissue _______. It is this that may limit short term intensive exercise.
3. The respiratory capacity of muscles following cessation of training has been shown to be less after a period of only _____________.

"What dolphins tell us about hydrodynamics"
1. Dolphins are capable of exceeding speeds of _____ ms-1 which is roughly _____times greater than that of a human sprinter.
2. The skeletal muscles of dolphins are capable of power outputs ranging from _____ watts/kg to _______ watts/kg. This is the same, greater, or less than that of other mammals?
3. Thrust generation in the dolphin is created by the tail____ through a process dependent upon _____forces rather than by viscous effects.