The Fluid Dynamics of Competitive Swimming

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Abstract

Nowhere in sport is performance so dependent on the interaction of the athlete with the surrounding medium than in competitive swimming. As a result, understanding (at least implicitly) and controlling (explicitly) the fluid dynamics of swimming are essential to earning a spot on the medal stand. This is an extremely complex, highly multidisciplinary problem with a broad spectrum of research approaches. This review attempts to provide a historical framework for the fluid dynamics–related aspects of human swimming research, principally conducted roughly over the past five decades, with an emphasis on the past 25 years. The literature is organized below to show a continuous integration of computational and experimental technologies into the sport. Illustrations from the authors' collaborations over a 10-year period, coupling the knowledge and experience of an elite-level coach, a lead biomechanician at USA Swimming, and an experimental fluid dynamicist, are intended to bring relevance and immediacy to the review.

1. INTRODUCTION

Dolphin kick: also known as the dolphin; an undulating underwater full-body motion analogous to the swimming motion of dolphins

Pull: the propulsive motion of the arms in a stroke, from in front of the head toward the feet

Recovery: the phase of the arm motion in which the hand moves forward at the end of the propulsive movement (i.e., the pull) to a position out in front of the head

High elbows: term used primarily to describe the bending of the elbows necessary for a swimmer to reach forward while simultaneously pointing the forearms down toward the bottom of the pool

In an epic moment in competitive swimming, Michael Phelps out-touched Milorad Čavić by 0.01 s to win the gold medal in the men's 100-m butterfly at the 2008 Beijing Olympics. This was the seventh of Phelps's record eight gold medals in the Beijing games and the fourteenth of his record total 18 career Olympic gold medals. Čavić again finished second behind Phelps in the 2009 World Championships and fourth in the 2012 Olympics.

The 2008 Phelps-Čavić finish spotlights the incredible complexity underlying the science of elite swimming. It came down to two men, one year apart in age, both born, raised, and trained in the United States (although Čavić has dual citizenship with Serbia). Čavić was 6 cm taller and 10 kg heavier than Phelps, but the race was decided almost literally by a fingernail. Indeed, there is photographic evidence indicating that Čavić touched the wall first. But the official ruling was that Phelps hit the wall harder and triggered the timer first.

Could Čavić have improved his propulsion just enough by more efficiently coordinating his biomechanics with the ensuing fluid mechanics? Or could he have reduced his drag ever so slightly so as to spoil Phelps's run at the record books? These questions point to the importance of technique in swimming and why so much research goes into identifying the so-called perfect stroke. Without even being aware of the existence of Profs. Navier and Stokes, a world-class swimmer inherently uses fundamental fluid dynamics principles to produce high thrust with minimum drag.

The science and technology of swimming are highly complex, with a myriad of variables from physiological to physical and psychological. As such, there is no one perfect stroke for all swimmers. But there certainly are universal principles that apply to swimming faster. It is the objective of this review to show how fundamental science, specifically fluid dynamics, and elite swimming are coming together.

2. A FEW KEY TERMS DEFINED

At the outset, it is instructive to provide a quick primer on some of the common terms of the sport. There are four strokes in competitive swimming today: the freestyle, backstroke, butterfly, and breaststroke, commonly known as the free, back, fly, and breast. The freestyle and backstroke are still occasionally referred to in the literature by the more traditional names, front crawl and reverse crawl. When swimmers are underwater at the start of a race or after a turn, they perform an undulating motion with their bodies called a dolphin kick, or simply dolphin. A swimmer is permitted to do the dolphin kick for the first 15 m of each leg of the competition in all strokes except the breaststroke. In the breaststroke, the swimmer is allowed only one dolphin kick at the start of each leg.

Regardless of the stroke, the pull refers to the part of the arm motion from the head toward the feet associated with propulsion. The catch is the initial part of the pull during which the swimmer sets up the arms and body to develop as much thrust as quickly as possible. Coaches frequently describe this to their swimmers in terms of trying to catch as much water with their arms and propel that water backwards toward the feet. The motion in which the hand moves forward from the hip to the start of the next pull (i.e., out in front of the head) is the recovery.

Particularly in the past 10 years, there has been a great deal of emphasis on high elbows. This can refer to the recovery phase of the freestyle stroke; the swimmer is taught to envision the elbow looking like the dorsal fin on a shark as the hand moves forward just above the water surface. More frequently, however, the term high elbows is used to describe how the arm needs to be positioned at the beginning of the catch. The objective is to get the forearms pointed straight down toward the bottom of the pool so that, throughout the pull, the swimmer is engaging as much water as possible. From a fluid dynamics perspective, the arm is a bluff body, and its motion toward the feet during the pull creates a drag force on the arm that is a forward propulsive force for the swimmer. The rationale for high elbows is to position as much of the arm in an orientation that maximizes the drag coefficient as far forward as is physiologically possible and to maintain that position as long as possible through the pull. As shown below, the concept of high elbows during the pull has been at the center of both the technique development and the science of competition swimming.

3. THE SEMINAL STUDIES ON COMPETITIVE SWIMMING

It appears that the first comprehensive treatise on swimming was written by Thévenot (1699) at the end of the seventeenth century. The purpose for swimming in that era was primarily to survive a shipwreck, although the military advantages of boarding an enemy vessel from the water were also identified. In terms of survival, Thévenot points out, in a section titled "To Swim with the Head erect towards Heaven," that "if we knew how to make use of it, there would not be so many drowned as there daily are." This is the precursor to the modern-day backstroke.

The first modern-day science-based textbook on swimming was written by the renowned US Olympic swim coach Doc Counsilman in 1968. He and his son wrote a second edition more than a quarter century later (Counsilman & Counsilman 1994). Counsilman was known as an innovator in the sport of swimming, having coached a number of Olympians, including Mark Spitz. In his book, Counsilman (1968) used film taken through an underwater viewing window to study the mechanics of his swimmers' strokes. He was one of the first to introduce fluid dynamics concepts to the sport. Indeed, the literature is sparse on the subject of human swimming hydrodynamics prior to Counsilman's landmark book. In spite of significant changes to stroke technique since then, Counsilman's work remains one of the most important references for both coaches and swimmers today.

In contrast, Lighthill (1971), in his review article on the hydrodynamics of aquatic animals, explicitly avoided the subject of "the feeble attempts of *Homo sapiens*" at swimming. Within that statement, Lighthill clearly identified the challenge of studying the fluid dynamics of competitive human swimming (see the sidebar, A Brief Glance at the Study of the Fluid Dynamics of Marine Animals). Humans, even Phelps, are incredibly inefficient in the water. As such, it is very difficult to identify the key parameters and understand the core dynamics in such a highly complex, multidimensional system. In a very real sense, competitive swimming is a classic engineering problem; it is important to understand and control the essential dynamics without getting overly distracted by the complexity. Ultimately, the clock is the final judge in the pool, but it is not a good diagnostic.

A BRIEF GLANCE AT THE STUDY OF THE FLUID DYNAMICS OF MARINE ANIMALS

Much of what is emerging in the science of competitive swimming has been spearheaded by biologists and engineers collaborating on the study of the swimming of marine animals. In the 1990s, Michael Triantafyllou and Dick Yue at MIT led an effort to build a robotic tuna, one of the first efforts in biomimetics. George Lauder of Harvard University and Frank Fish from West Chester University have studied the fluid dynamics of swimming from fish to dolphins and whales. Lauder pioneered the use of DPIV in studying the wakes of fish, whereas Fish (the marine biologist) has led an effort to measure flow around dolphins. He has also partnered with Alexander Smits of Princeton University to study and robotically model the thrust produced by the undulating fins of manta rays. Rajat Mittal of Johns Hopkins University has worked with Fish and Lauder on computationally studying vortex-induced thrust associated with swimming eels and fish. Mittal's work has actually produced an ongoing dialogue in the competitive swimming community as to whether there is an optimal Strouhal number for the human dolphin kick.

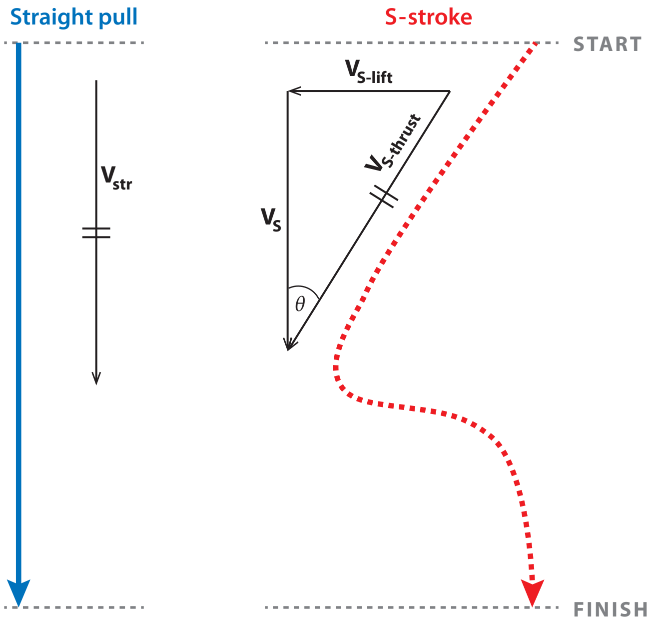

Figure 1

Comparison on the hand trajectories of an S-stroke (*right; red dashed arrow*) and a straight pull (*left; blue solid arrow*). The vector triangle shows the velocity of the S-stroke pull broken into streamwise and transverse components in the swim or thrust direction and the cross-body or lift direction. Note that the net stroke lengths and the arm speed are the same for both strokes (i.e., $|V_{str}| = |V_{S\text{-thrust}}|$).

4. THE S-STROKE AND ITS EFFECT ON THE SPORT

To set the stage for the remainder of this article, we turn to a concept first introduced by Counsilman (1968, 1971) and Brown & Counsilman (1970), which is still taught in competitive swim clubs across the world today. This is referred to as the S-stroke. **Figure 1** shows a top-view schematic illustrating the trajectory of a right hand executing an S-stroke compared to what is called a straight pull. By way of reference, at the top of the S-stroke, the right hand would be roughly outboard of the shoulder line. As the swimmer pulls, the hand would sweep inward toward the midline of the body. The last part of the pull would entail an outward sweep of the hand past the hip.

Developers and proponents of the S-stroke believed that by pulling diagonally across the body, the swimmer combines the effects of bluff body thrust of the hand and forearm moving antiparallel to the swimming direction and the hydrodynamic lift associated with the transverse component of the motion of the hand. The argument was that the total thrust of the S-stroke is greater than that of the straight pull.

One can do a simple analysis to show that the S-stroke is not likely to be more effective than the straight pull. Let us assume that the swimmer's arm speed during the pull is essentially the same regardless of a straight pull or an S-stroke and that, for simplicity, the drag coefficient of the arm and hand is unity. Finally, let us assume that the lift coefficient of the hand will also be unity, a generous assumption in favor of the S-stroke. Now if θ ranges between 20° and 30°, then the arm speed in the swimming direction, V_S, will be 6% to 13% slower than for a straight arm pull, V_{str}, resulting in 12–26% less thrust.

For a swimmer doing an S-stroke, the lift generated by the transverse motion across the body must make up for that lost thrust. For a 20° to 30° inward sweep, the transverse hand speed, $V_{S\text{-lift}}$, will be 34% to 50% of the straight pull speed. But keep in mind that the hand is only one-quarter to one-third of the length of the arm. Assuming the area of the hand is one-third of the area of the arm, then for a 20° arm sweep, the hand generates only 4% additional thrust, for a net loss of 8% in comparison to a straight pull. For the 30° sweep, the net loss in thrust for the S-stroke is ~18%. And this assumes, of course, that the hand works as effectively as a NACA airfoil. The only way to make up that difference would be for the arm to move 5–10% faster. But then the benefits of the S-stroke are lost as the swimmer must work much harder to generate the same thrust.

Over the past decade, elite-level swimming coaches and their swimmers have moved away from the S-stroke, if for no other reason than the swimmers using the straight pull were winning races and those using the S-stroke were not. At the local club level, however, the S-stroke is still being widely taught. This example illustrates how fluid dynamics incorrectly or incompletely applied in a highly complex, multidegree-of-freedom sport can alter the sport. It also demonstrates, however, how proper application of the same fluid dynamics can be used to advance the sport. The following sections highlight different approaches that researchers have used over the years to try to connect science to the sport of elite competition swimming. The sections are organized to also show how diagnostic capabilities have advanced and have created space for more accurate and insightful study of the sport.

5. OBSERVATION-BASED WHOLE-BODY APPROACHES

From the seminal work of Counsilman (1968) to the present, much of swimming research has been done through careful observation by practitioners and experts in the sport. There are works focused on the biomechanics of swimming, including Miller (1975), Clarys (1978), Hay (1988), Kolmogorov et al. (1997), Toussaint et al. (2000), Gettelfinger & Cussler (2004), and Polidori et al. (2006). There are also physiologically focused studies, such as Faulkner (1968), Magel (1971), Holmér (1972), and Troup (1999). These holistic approaches are in part a recognition that the complexity and nonlinearity of fluid dynamics necessitate that swimming be studied at the systems or whole-body level. But it also recognizes that there is much of great importance that can be brought to the sport simply by highlighting some key fundamentals.

Comprehensive overviews, such as those of Toussaint et al. (2000), Miller (1975), and Kolmogorov et al. (1977), have attempted to connect various fluid dynamics concepts to physiology and best swimming times. Other researchers maintained a whole-body approach but looked at specific thrust and drag mechanisms acting on swimmers. For example, Clarys (1978) attempted to decouple drag components acting on the body, whereas Polidori et al. (2006) specifically examined viscous drag effects.

Embedded in these works lie many elementary concepts that are foundational to fast swimming. The most important, although seemingly trivial, is the notion that a swimmer's speed is equal to the distance that swimmer travels per stroke multiplied by the swimmer's stroke rate. That is,

$$\text{speed} = \text{distance/stroke} \times \text{stroke rate}. \tag{1}$$

This was explicitly addressed by Craig & Prendergast (1979). The entire sport of competitive swimming comes down to this maxim: Technique combined with body position in the water ensures that the swimmer goes as far as possible for each stroke. The challenge to the swimmer is to maintain technique and body position at as high a stroke rate as possible.

Maximizing distance per stroke is a combination of maximizing thrust and minimizing drag. There has been some work on streamlining to minimize drag (e.g., Lyttle et al. 1998, Naemi et al. 2010). But the swimming community universally understands this concept. The most important coaching/technique issue in this regard is getting the swimmer to swim as flat as possible: in aerodynamics terms, getting the swimmer to swim in as much of a streamlined position as possible at zero angle of attack.

In the context of maximizing thrust, the fluid dynamics principle that has had an impact on the sport is bluff body drag. Specifically, during the pull, the bluff body drag on the arm is pointed forward in the thrust direction. This is the concept that thrust associated with the pull is drag backwards. The understanding of this principle has led to the more effective application of the high-elbows pull described in Section 2.

One topic explored in detail by Larsen et al. (1981), Miller (1975), and Vennell et al. (2006), and included in the review by Toussaint et al. (2000), is that of wave drag. In their discussion, Toussaint et al. (2000) identified the Froude number as the critical parameter against which to compare swimmers. But more importantly, they noted that the hull speed is a critical parameter, determined from the formula

$$V_{\text{hull}} = 1.248 \times \sqrt{4}, \tag{2}$$

where V_{hull} is the hull (i.e., swimmer's) speed in meters per second, and $\sqrt{H}$ is the square root of the height of the swimmer in meters. Recall that when V_{hull} is achieved or exceeded, the swimmer is, in a sense, surfing his or her own bow wave. When this happens, wave drag drops dramatically, and the speed can increase equally dramatically.

The reason wave drag is so interesting is that the hull speed of a human swimmer turns out to be around the same speed as world-class swimming speeds for the middle and distance races. As a reference data point, Sun Yang, the winner of the men's 400-m freestyle event in the 2012 Olympics, is 1.98 m tall. His hull speed then is 1.76 m/s. This translates to 56.94 s per 100 m in a race. His gold medal time in the 400-m freestyle was 3:40:14, corresponding to an average of 55.04 s per 100 m, 3.3% faster than his hull speed. But if one considers that the diving start and each push off the wall reduce the time per 100 m by approximately 1 s, it is clear how important the hull speed is. Or, more precisely, it is clear how important it is to develop a technique that will allow the swimmer to overcome wave drag.

As an interesting aside, Gettelfinger & Cussler (2004) provided a singularly unique study with the sole objective to determine if a swimmer would swim any faster in a fluid more viscous than water. This study drew quite a bit of attention in the swimming world and in the popular media, perhaps because one of the authors was an elite swimmer (Gettelfinger swam in the 2004 US Olympic Trials) and because the work was done in an Olympic year. What is fascinating is that the authors were able to acquire permission to fill an entire Olympic-size swimming pool with a viscous guar-gum solution that was twice as viscous as water. It should not come as a surprise to the readers of this article that in tests of 16 swimmers, including Gettelfinger, doubling the viscosity had no effect on swimming speed.

The obvious next level of detail in swimming research is to study individual strokes. Schleihauf et al. (1988) and Hellard et al. (2008) discussed all four of the competitive strokes, whereas Schleihauf (1974), Keskinen & Komi (1988), Nakashima (2007), and Yanai (2001, 2004) presented examples of papers focused on the freestyle. One of the open questions regarding the freestyle and backstroke, as addressed, for example, by Yanai (2001, 2004), is how much the body should roll along the long axis from the recovery through to the pull. The issue is whether swimmers can take advantage of torque generated from the displacement of their buoyancy and weight vectors.

A review of the literature on competitive swimming reveals a compendium of studies on the different competitive strokes. Smith et al. (1998), Chollet et al. (2008), and Klentrou & Montpetit (1992) studied the kinematics and energetics of the backstroke. Similar studies for the breaststroke were conducted by Vilas-Boas & Santos (1994), Coleman et al. (1998), Thompson et al. (2000), and Chollet et al. (2004). Togashi & Nomura (1992), Sanders et al. (1995), and Seifert et al. (2007) provided examples of work done on the butterfly. It is not surprising that there is an extensive body of literature on shoulder injuries related to the butterfly stroke. This is, of course, outside the scope of this article.

6. COMPUTATIONAL FLUID DYNAMICS APPROACHES

Moin & Kim's (1982) direct numerical simulation study on turbulent channel flows was among the first numerical studies in which complex, unsteady, turbulent flows could be calculated with high degrees of spatial and temporal resolution. With the beginning of the computational fluid dynamics (CFD) era, Bixler & Schloder (1996) conducted one of the earliest CFD studies to specifically try to address the fluid dynamics of human swimming. In that study, they used Fluent to study two-dimensional flow around a circular plate as a simplified model for the hand. They expanded their capability using a three-dimensional code to actually study flow over a geometrically accurate hand (Bixler & Riewald 2002). In both these papers, the hand models were subjected to steady laminar flow, and the full arm, not to mention the full body, was not included in the computation.

The full hand-arm model was tested both experimentally in a wind tunnel and computationally using Fluent by Gardano & Dabnichki (2006). Examples of other experimental studies focused specifically on the arm and hand include those by Berger et al. (1995) and Minetti et al. (2009).

Toward the end of the twentieth century, faster computers and the demand for solutions to increasingly complex problems drove rapid advances in computational methodologies. For example, Johnson et al. (1994) and Chen et al. (1995) were among the first to employ surface markers to track moving free surfaces to model tsunami impacts on buildings and shorelines. From a fluid dynamics perspective, the dynamic motion of a solid body (i.e., the swimmer) with water at the free surface is exactly the class of problems that requires these new computational methods. Different computation approaches to studying swimming have been presented by Nakashima (2007), Mittal et al. (2006), and Marinho et al. (2009).

Von Loebbecke & Mittal (2012) revisited the problem of computing flow around the arm and hand using a finite-difference-based immersed boundary method. That technique was described in detail by Mittal et al. (2006). Comparing detailed flow information gained from their computations with videos and corresponding swimming speeds of elite swimmers, von Loebbecke & Mittal (2012) drew an interesting conclusion. They found that the concept of hydrodynamic lift, put forward by Counsilman (1968, 1971), was in fact an important part of propulsion in the freestyle and backstroke. They noted, however, that "exaggerated sculling motions," presumably the S-stroke, actually reduced net thrust.

One important element of competitive swimming involving the whole body that is ideally suited for advanced computational methodologies is the dolphin kick. Its importance in competitive swimming lies in the fact that a swimmer can use the dolphin kick for up to 15 m of the pool on each leg of a freestyle, backstroke, or butterfly race. The 15-m limit applies regardless of whether the pool length is 50 m (long course) or 25 m (short course). The limit was imposed after the 1988 Olympics when US swimmer David Berkoff broke the world record in his preliminary heat of the 100-m backstroke by going ~30 m under water on the first 50-m leg. In the 2004 Olympics, Japanese breaststroker Kosuke Kitajima was caught on network television dolphin kicking on his way to Olympic gold. Protests were disallowed because the Olympic officials, looking from above the water (the camera was under water), did not see the infraction.[1]

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[1] Today, the rules have been changed to allow breaststrokers one dolphin kick for each leg of their races. This was a direct result of the Kitajima controversy. But the story has not ended; elite breaststrokers are purported to throw more than one dolphin kick per leg (Peters 2012).

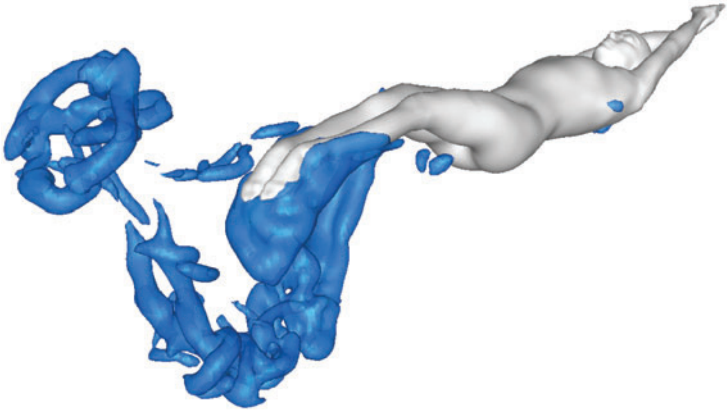

Figure 2

Three-dimensional vorticity contour plot from von Loebbecke et al. (2009a) of flow generated during a dolphin kick. A strong coherent vortex ring is clearly visible on the left side of the image.

There have been numerous detailed studies of the dolphin kick in recent years, including von Loebbecke et al. (2009a,b), Naemi et al. (2010), Cohen et al. (2009, 2012), and Webb et al. (2012). Works by von Loebbecke et al. (2009a) and Cohen et al. (2009) are examples of the application of advanced computational techniques to swimming. A key advantage of this type of work, as pointed out by von Loebbecke et al. (2009a), is the ability to compute mechanical efficiencies, the ratio of useful (thrust-producing) mechanical work done by the swimmer to the total mechanical work expended. **Figure 2** shows an example of the highly resolved flow around a dolphin-kicking swimmer. Even with this enhanced capability to study the fluid dynamics of swimming, the ability to truly model the complex fluid boundary conditions has not yet been achieved. In addition, connecting the computation biomechanics to the actual human physiological energy expenditure remains elusive.

7. EXPERIMENTAL TOOLS AND TECHNIQUES

Ultimately, the challenge to understanding the fluid dynamics of swimming is knowing exactly what the water is doing as the swimmer swims through it and what the resulting forces are the swimmer generates. Since Counsilman (1968), visual observation has been an important, if not the dominant, diagnostic tool in swimming science. What appears on film/video, coupled with the stopwatch, has strongly shaped the sport. However, what should be clear at this point is that video is a highly subjective tool. And dynamically significant, accurate, real-time, noninvasive diagnostics have been a holy grail for swimming scientists.

One of the early innovations in force measurements was the measurement of active drag system developed by Hollander et al. (1986). This system consisted of a set of submerged paddles, each of which was fitted with load cells. As a swimmer pushed off these paddles, load cells mounted in the paddles measured the thrust generated or drag overcome by that swimmer. The likelihood that the swimmer's stroke was modified in this measurement technique is obvious. But this was one of the most advanced systems available to the sport for quite some time.

In the past decade, systems using accelerometers and other on-board dynamic measurement devices have been developed (Ohgi et al. 2002, Davey et al. 2008, Nakashima et al. 2010, Bächlin & Tröster 2012). The innovation behind these systems is their ability to remotely transmit data

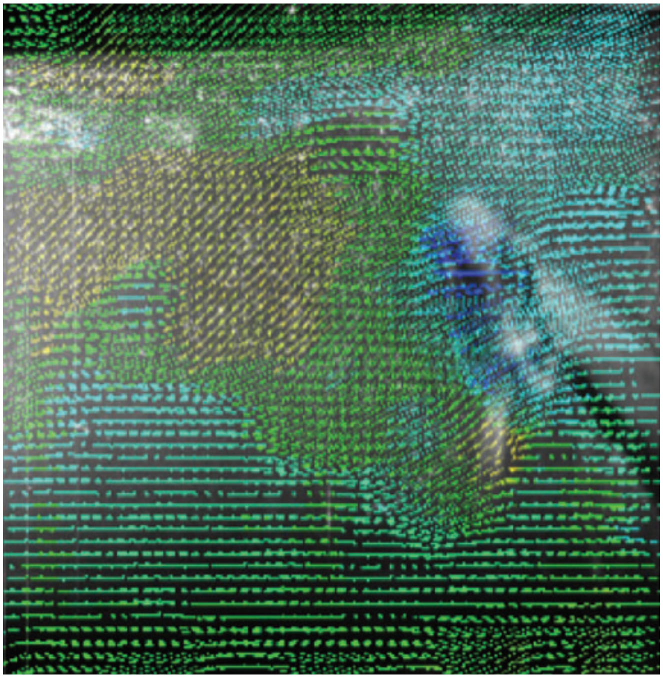

Figure 3

Instantaneous digital particle image velocimetry vector field showing the flow generated by Megan Jendrick's breaststroke kick. Note the dark blue vectors pointing away from the bottom of her right foot.

through an air/water interface. Although they can be used to track a number of body parts, they are as yet unable to provide the same whole-body resolution as the advanced CFD studies.

A major advance in whole-body experimental methodologies has been the adaptation of digital particle image velocimetry (DPIV), first described by Willert & Gharib (1991), to competitive swimming. Ground-breaking studies on the fluid dynamics of fish swimming, led by Drucker & Lauder (1999) and Liao et al. (2003), paved the way for the application of DPIV to human swimming. In a more traditional application, Yamada et al. (2006) used PIV on a hand model in a laboratory setting. The first attempts at applying DPIV to live human swimmers were done by Wei et al. (2004), Legac et al. (2008), and most recently Hochstein & Blickhan (2011).

Figures 3 and **4** show examples of DPIV measurements of flow around swimmers, taken as part of the study by Legac et al. (2008). **Figure 3** shows flow from the feet of Megan Jendrick, 2000 Olympic gold medalist in the women's 100-m breaststroke and 4 × 100-m medley relay, as she is doing a breaststroke kick. This is a single still frame taken from a movie in which small air bubbles were used as seeding particles. Swimmers were filmed in a flume at the US Olympic Training Center using a high-resolution DPIV camera. The capture rate for DPIV image pairs was 15 Hz, and the field of view was approximately 1 m^2. A detailed description of the methodology is provided by Legac (2008).

In this single frame, Jendrick's feet can be observed just as she is beginning the power stroke of her kick. She is swimming to the right, and her body has passed out of the field of view. Only her ankles and feet appear in this frame. We note the dark blue vectors pointing straight back from the bottoms of her feet; vector colors were scaled on the streamwise velocity component. This particular image was used in an analysis of breaststroke kicking, leading to an understanding that

Figure 4

Instantaneous digital particle image velocimetry vector field showing the flow generated by Ariana Kukors's freestyle stroke. Note the high elbow position and the dark blue vectors pointing away from her right hand and arm.

the thrust generated during the kick was probably best thought of as having the feet push water straight back in the thrust direction.

Figure 4 is another single still frame showing an overlay of the original video frame and the corresponding flow vectors. In this example, flow associated with Ariana Kukors's freestyle pull is highlighted. In this image, Kukors's head and upper torso are visible. The key feature of **Figure 4** is the dark blue vectors extending from Kukors's right hand as she engages the water early (i.e., uses a high elbow) and pushes water backwards. Kukors's freestyle was part of a winning combination that led her to break the world record in the women's 200-m individual medley (twice!) as she took gold in that event at the 2009 World Championships.

It was explicitly the full video sequence from which the single image in **Figure 3** was taken that led Kukors's coach to modify her breaststroke kick. This in turn helped Kukors drop 3 s in her 100-m breaststroke time and was an important step in her route to world record success in 2009.

As part of this same effort, a force balance was developed to directly measure forces generated by swimmers. This is described in Legac (2008) and shown schematically in **Figure 5**. The balance consists of a steel frame. The swimmer pushes on either bar A-A, below the surface, or bar A′-A′, at the surface. In the figure, a swimmer is shown doing an underwater dolphin kick and is pushing on bar A-A. Load cells on the frame elements provide time-resolved force traces that are recorded using LabView. By synchronizing the video with the force traces, one can correlate a swimmer's movements with the force output. We note that the swimmer can also be tethered to one of the crossbars, allowing force measurements of the full stroke.

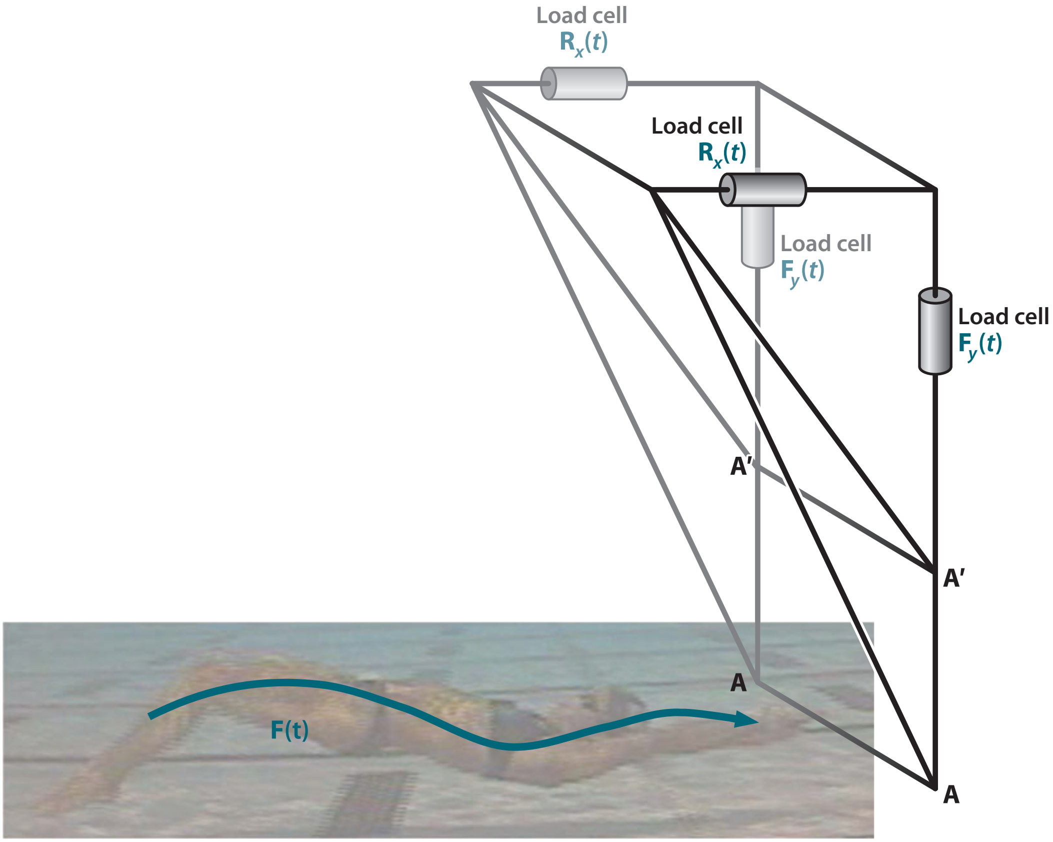

Figure 5

Schematic drawing of the two-component force balance used to measure forces generated by swimmers. The swimmer pushes on bars on a steel frame (*black lines*), either bar A-A below the surface or bar A′-A′ at the surface.

Figure 6 shows a single frame from a video recording of Kukors's flutter kick. In this video, Kukors is kicking against the force balance, which is out of view to the left. The signal trace under the video image is the time trace of Kukors's force. Time is across the horizontal axis, and the force generated is plotted on the vertical axis. The vertical line at $t = 0$ in the middle of the time trace corresponds to the time that particular video frame was recorded. So the force output of 30 pounds at $t = 0$ is the force Kukors generated while she was kicking downward with her left leg.

What is particularly interesting about the time trace is the smaller peaks between the larger peaks. The larger peaks are spaced roughly 0.25 s apart, with a peak force generally between 20 and 25 pounds. Each peak corresponds to the downward kick of one of Kukors's legs. As noted, the peak at $t = 0$ corresponds to a left leg kick. The peak to the right of that is a right leg kick. The one immediately after that is another left leg kick, and so on.

One can see smaller peaks between the larger ones. These, it turns out, are forces generated when Kukors kicks backwards, or up toward the water surface. The ability to quantify the force generated during this reverse kick shows the power of the measurement technique. Clearly this force is significantly less than that generated during the downward or forward kick. Although Kukors reported that she could feel the effort associated with the upward reverse kick, it felt

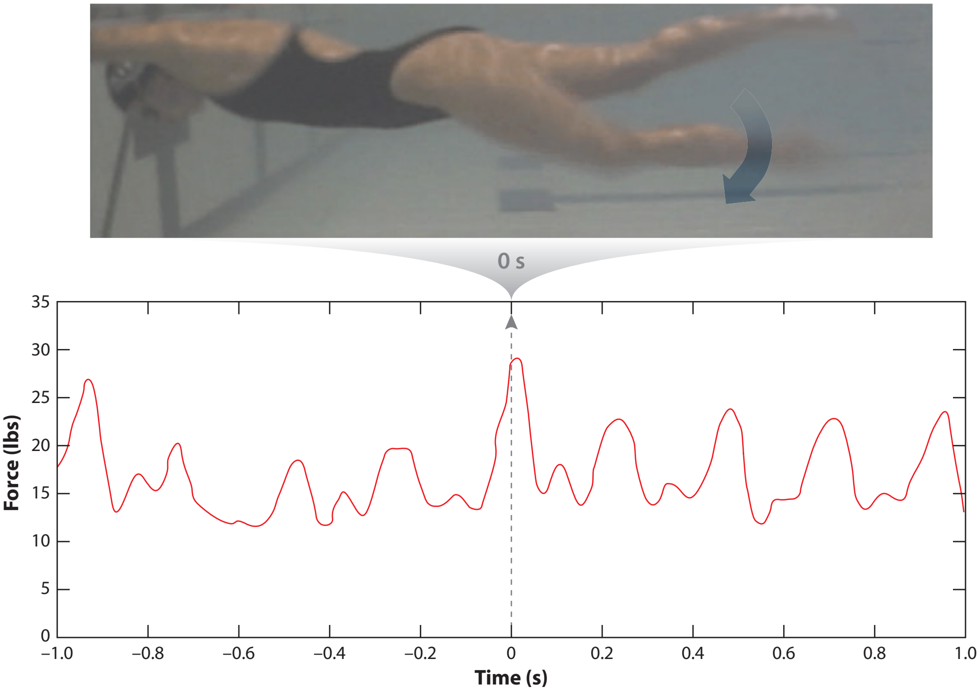

Figure 6

Instantaneous video image of Ariana Kukors flutter kicking with the force readout below. The center of the plot, $t = 0$, corresponds to the video frame shown. Kukors is generating a force of ∼30 pounds with the downward kick of her left leg, as indicated by the shaded arrow placed over her left leg.

different when she was doing backstroke. This was of course because gravity is aligned with the reverse kicking direction (i.e., downward) in the backstroke but acts against the upward reverse kick on the freestyle kick. Data such as those shown in **Figure 6** create the opportunity for a coach and swimmer to discuss the relative benefits of generating this additional thrust at the cost of using energy that might be needed at the end of a race.

8. NEXT STEPS

Throughout this review, one can see an evolution from a science based heavily on indirect data (i.e., experts observing swimmers; clocking swim times or stroke rates; and then applying intuition, experience, and varying degrees of scientific understanding) to the introduction of advanced computational and experimental diagnostics. Although still imperfect, the capability now exists to either directly compute or noninvasively measure critical dynamic information with high spatial and temporal resolution. The study of the fluid dynamics of swimming is growing from empirical observation and interpretation to direct measurement (either computational or experimental) backed by sound fundamental physics.

Energetics, the linking of biomechanics, fluid dynamics, and human physiology, is the next great challenge in the science of competitive swimming. Early studies along these lines include Holmér (1974), Miyashita (1974), and Wakayoshi et al. (1992a,b). Barbosa et al. (2008, 2010) have provided an overview of the state of the art and ongoing challenges. Wang & Wang (2006), Toussaint & Truijens (2006), and Zamparo et al. (2005) applied energy concepts to the analysis of specific strokes or events.

In engineering terms, energetics is equivalent to computing a swimming efficiency. The numerator is generally related to the mechanical work done to propel the swimmer through the water. The denominator is either the total energy available in the swimmer or the amount of energy expended by the swimmer. The energy expenditure is a physiological parameter and probably the hardest to directly quantify. But the ability to accurately quantify the energy directly contributing to propulsion has been, until recently, equally problematic.

As an illustration of the importance of energetics, let us consider the performance of Jendrick in the 2005 World University Games.[2] Jendrick won gold in the women's 50-m and 100-m breaststroke events, breaking the meet records in both events. However, she finished eighth in the 200-m breaststroke event. Her 50-m split times in the 200-m race were 34.74 s, 38.29 s, 39.15 s, and 39.56 s. Even accounting for the first 50 m being significantly faster because of the diving start, Jendrick got significantly slower from the start of the race to the finish. She simply could not sustain the energy output that she could generate in the shorter distance events.

It turned out that at that time, Jendrick believed that she should continue her breaststroke pull until her hands were roughly even with her waist, rather than finishing around the chest as is done by most breaststrokers today. What she did not understand was that as she completed her pull, her upper body was almost vertical in the water. So although she may have been generating thrust at the end of the stroke, she was doing so against a tremendous amount of drag. It was only natural that she would get slower in the longer races because of fatigue. After 2005, Jendrick changed her stroke so that her body followed a flatter trajectory and her pull did not extend so far down along her torso. After failing to qualify in 2004, she returned to the Olympics in 2008, winning a silver medal in the women's 4 × 100-m medley relay.

The ability to measure energy output can actually be derived from high-resolution, high-speed video. By tracking a point (e.g., the goggles or nose) on the swimmer's body from frame to frame, one can generate a trace of the swimmer's position with time. First and second derivatives of that position versus the time trace of course provide velocity and acceleration. The mass of the swimmer can be readily measured, so the instantaneous net thrust produced by the swimmer can be directly determined from the video record. The product of velocity and thrust is the useful power or rate of work done by the swimmer. Examples of this type of image analysis are shown in **Figures 7** and **8**.

Time traces of speed, acceleration, and power were generated for the dolphin kick of two swimmers, Kukors and a club swimmer, Lauren, using the same videos from the studies in Legac et al. (2008). These are shown in **Figure 7*a*,*b***, respectively. Similar to the DPIV vector fields shown in **Figures 3** and **4**, the framing rate of the camera in this study was 15 Hz with a spatial resolution of 1,000 × 1,000 pixels over a field of view of approximately 1 m^2. The swimmers were swimming against a current in a flume that was set to a speed slightly lower than their swim speed. In this way, the motion of the swimmer in the field of view could be effectively compressed. The speed of the flume has been added back to the measured swimming speed plotted in **Figure 7**.

In comparing the two swimmers, what is immediately apparent is that Kukors is much more efficient than Lauren. Kukors is faster despite a lower kicking frequency and lower peak thrust. Although Lauren has larger peak accelerations, she is not able to maintain speed. The coaching

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[2] Members of the United States team at the 2005 World University Games were the top two collegiate finishers in each event from the 2004 Olympic Trials who did not make the Olympic team. Typically, this would have been the third and fourth place finishers in each event at the Olympic Trials.

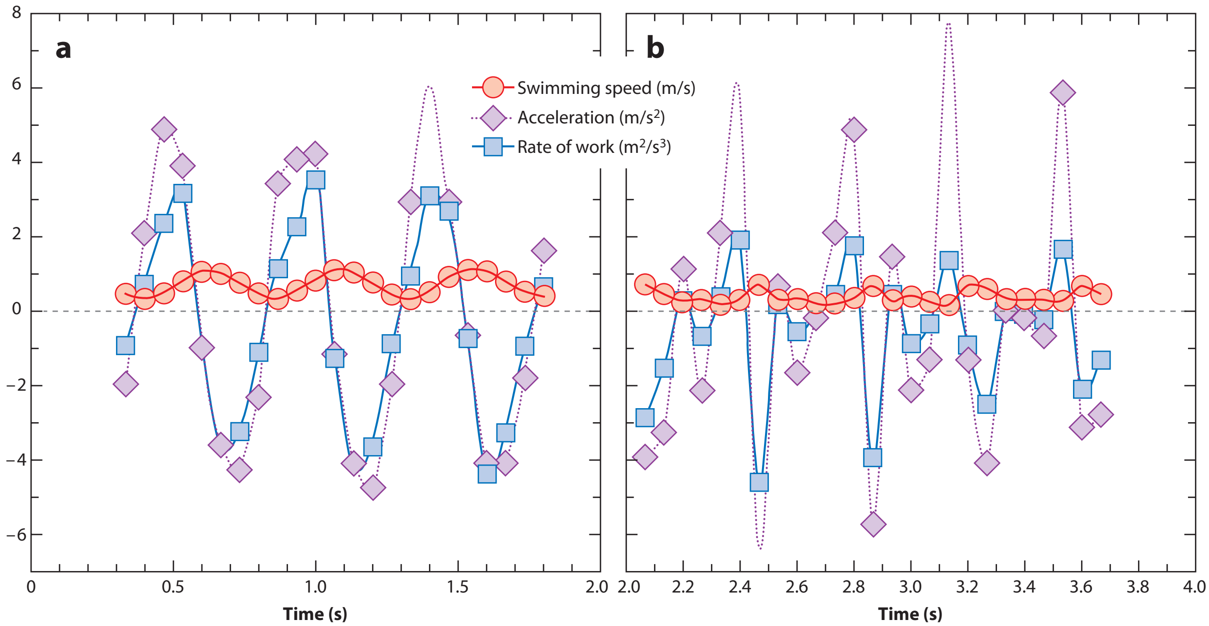

Figure 7

Time traces of swimming speed, acceleration, and rate of work associated with dolphin kicking for (*a*) Ariana Kukors and (*b*) a club swimmer, Lauren. Note the sinusoidal shape of the world record holder's energetics.

takeaways then would be to examine Lauren's body position to minimize drag and the timing and coordination of her dolphin kick to maximize thrust.

Perhaps the coaching opportunities made available by this type of analysis are best seen when it is applied to the competition strokes. **Figure 8**, for instance, includes time traces of speed, acceleration, and useful power for the breaststroke of Jendrick. These data are taken from the same DPIV video record as the vector field shown in **Figure 3**. The experimental method was also the same as for the dolphin-kicking studies. The key difference here is that the breaststroke pull and kick are much more impulsive than any aspect of the dolphin kick. Consequently, an accurate analysis of the breaststroke probably requires higher temporal resolution. For the data shown in **Figure 8**, however, the camera framing rate was also 15 Hz.

The salient feature of the time traces in **Figure 8** is that there are two positive peaks in both the acceleration and power for each of the two strokes. The first pair of peaks is centered at approximately 0.5 s and 1.2 s, and the second pair is centered at approximately 2.1 s and 2.7 s. The first peak in each pair (i.e., the peaks at approximately 0.5 s and 2.1 s) corresponds to the pull, and the second peak in each pair corresponds to the kick. One can see that Jendrick's speed decreases between ∼0.7 s and ∼1.0 s and again between ∼2.2 s and ∼2.5 s. These decelerations correspond to the phase of the stroke when Jendrick completes her pull, and her head and shoulders rise up out of the water for her to take a breath; this initiates the recovery phase of the stroke. This high drag posture causes her to slow down. Once she has taken a breath, she dives back into the water and executes a breaststroke kick. This combined motion of resubmerging and kicking is responsible for the second of the acceleration peaks and corresponding power peaks for each stroke seen in **Figure 8**.

Although it is not immediately obvious, elite swimmers essentially choreograph their entire race. At any point in the pool, they know the number of strokes they should have completed and

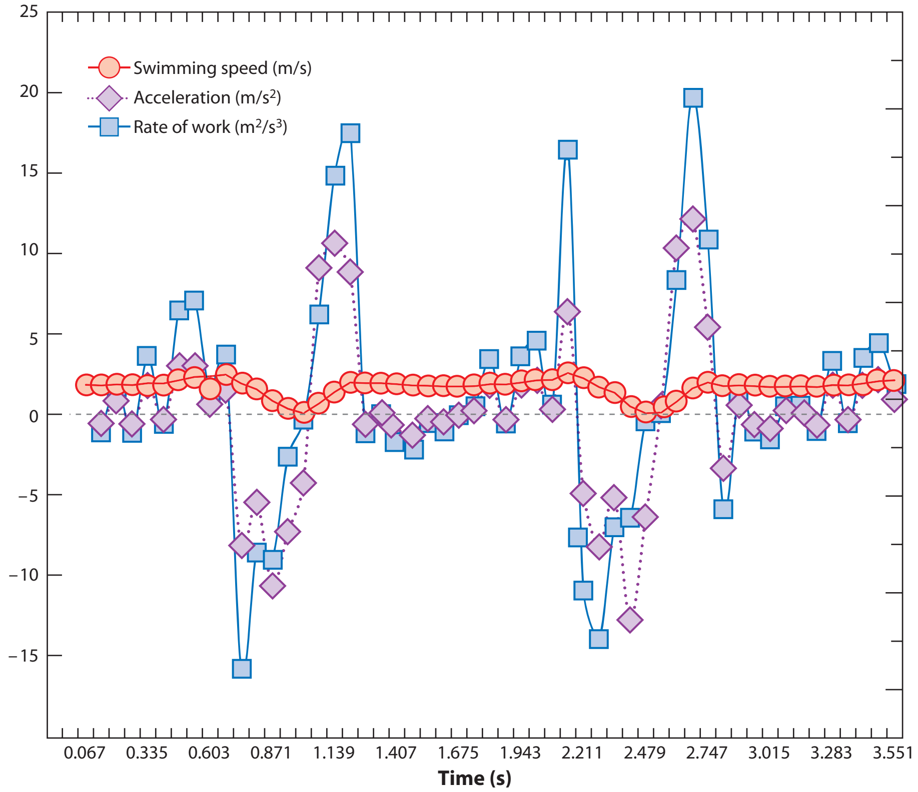

Figure 8

Time traces of swimming speed, acceleration, and rate of work associated with the breaststroke for Megan Jendrick. Data for two consecutive strokes are shown. We note that there are two thrust and power peaks for each stroke, one for the pull and one for the kick. The negative thrust and power result from deceleration during the breath phase of the stroke.

the time it should have taken them to get there. Data such as those shown in **Figure 8** can be used as a tool to highlight stroke variability; notice that Jendrick was not as effective in her pull on the first stroke in comparison with the second. For an elite-level swimmer like Jendrick, it is likely that she would have been able to articulate what went wrong. But this tool provides a science-based reason for assessing what the correct stroke should look like.

The ability to conduct temporally resolved analysis of speed, thrust, and power then represents a powerful tool in the study of competitive swimming. It is now possible to evaluate swim technique in terms of any of these three parameters at any point in the stroke. In so doing, the swim scientist can now provide the coach with rigorous physics-based insight into why certain techniques are better than others.

9. CONCLUSIONS

Above we provide an overview of many of the key researchers and contributions to the art and science of elite-level competitive swimming. From the highly insightful observations made in the days when film and a stopwatch were pretty much the only technologies available to ongoing advancements in computational methodologies and experimental diagnostics, the opportunities for far greater understanding and improved technique are emerging. At the end of the race, however, the only diagnostic tool that matters is the official clock. The fastest time will always beat the most elegant fluid mechanics measurements, unless the swimmer in the measurements is also the one with the fastest time.

SUMMARY POINTS

1. Competitive swimming comes down to high stroke efficiency at a high rate while simultaneously minimizing drag. The operative formula is swimming speed = distance/stroke × stroke rate.
2. For all four competitive strokes, the propulsive force generated by the arms is dominated by bluff body drag. It is incumbent on the swimmer, therefore, to engage as much of the arm perpendicular to the swimming direction (i.e., pointed straight down at the bottom of the pool) as early in the stroke as possible. This is the underlying principle behind the concept of high elbows.
3. The overall drag on the swimmer can be minimized by keeping the body in as much of a streamlined posture as possible throughout the race. This includes keeping the entire body, including the head, aligned with the spine and keeping the body horizontal in the water.
4. Wave drag can be a deciding factor, particularly in the longer races. Technique is essential to enable the swimmer to reach a speed that overcomes wave drag.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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