BIOMECHANICAL RESEARCH IN SWIMMING: PAST, PRESENT AND FUTURE

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Competitive swimming techniques used by today's swimmers have evolved mainly from imitation of previous or current champions. Swimmers may actually see and copy existing techniques as their careers develop or the coach may teach these observed movements. This imitation process continues to produce successful competitors and has become the popular method for achieving swimming proficiency. Improvements in swimming mechanics can be, and often are, the result of human ingenuity and trial and error by active swimmers and coaches. Our ability to help swimmers understand swimming more than they helped us understand it was limited as long as we continued to guess at the mechanical causes for how the body moves through the water. We are no longer guessing. We have a history of inquiry in swimming mechanics, and we are profiting from the results. The activities of researchers in the biomechanics of swimming are recorded in the literature, and a survey of it reveals the abundance of information we have at our disposal.

Doris Miller (1975) wrote an excellent review of the literature in her chapter, Biomechanics of Swimming, contained in Volume 3 of Exercise and Sport Sciences Reviews. Since that 1975 publication, the proceedings from the Second and Third International Symposiums on Biomechanics in Swimming have been published and contain many additional works. Miller's extensive bibliography can be supplemented with sources dating into the 1980's in Jim Hay's Bibliography of Biomechanics Research, which contains over 300 references for biomechanics of swimming literature (Hay, 1981).

T.K. Cureton's 1974 keynote address at the Second International Symposium in Brussels focused on a literature review concerned with factors governing success in competitive swimming. His bibliography includes biomechanical and physiological investigations (Cureton, 1975).

Jan Clarys' 1978 keynote address at the Third Symposium in Edmonton, Canada, contained a thorough overview of hydrodynamic variables and human morphology in swimming. His numerous references reflect the diversity of investigations directed toward swimming drag and propulsion (Clarys, 1979).

In light of these recent and most informative reviews that are readily available to us, I have focused my attention here on highlighting selected aspects of the research in the biomechanics of swimming. My objective is not to report specific research findings, but rather to identify what has been, and is, taking place in swimming biomechanics, and what path future research might follow.

One of the earliest systematic studies of swimming was reported in 1930 by a pioneer in swimming research, Peter Karpovich (1930). It was apparent that a swimmer could maintain an average constant velocity over a distance, but Karpovich was interested in the changes in velocity occurring within a single stroke cycle. He devised an apparatus called a Natograph which registered the progression of a swimmer every one fifth of a second. It consisted of a revolving drum around which a line was fastened and attached to the swimmer's waist or to a floating tripod over the swimmer, and a revolving contact switch to mark time intervals on a kymograph. As the line was pulled by the swimmer it revolved the drum. Graphs indicating variations in velocity within the stroke were plotted from the kymograph recordings. Four strokes were examined: the back crawl, the breaststroke, a fast and slow front crawl, and an English side-overarm. At that time, neither the butterfly breaststroke nor the dolphin butterfly were known. He identified distinct patterns of acceleration and deceleration for each of these strokes, indicating that the more variable the speed within a stroke, the more energy-consuming it was.

A few years later Karpovich (1933) looked at the resistance encountered by the body when it was towed through the water in prone and supine positions at speeds ranging from 1 to 8 ft./sec. At that time, although resistance data from studies on ship models were available, no information existed for the human body traveling through water. He measured the resistance by a device called a Resistograph which employed an electric motor, a towing cord directed through a pulley system and attached to a calibrated spring. The spring was then connected to a lever which recorded changes in spring length on a kymograph. From the "Resistogram" towing speed could be calculated simultaneously with water resistance in pounds. He tested 14 swimmers (including three "athletic type" women) each towed through the water 60 to 200 times. His results indicated that, due to changing body positions, variations in resistance occurred in the same subject at any given speed. In this early paper he pointed out the three factors contributing to the total resistance encountered by a swimmer: skin friction, eddy resistance, and wave-making resistance. From this work, Karpovich presented one of the earliest attempts at modeling human swimming performance. He developed resistance formulas for predicting the resistance for swimmers being towed in prone and supine positions. Two years later, Karpovich's (1935) interest in the quantitative aspects of swimming led him to research the relative values of arm and leg action in the front crawl. He measured velocity using arms alone, legs alone, and arms and legs together. His results indicated that there was a fairly stable relationship between arm propulsion and leg propulsion as they contribute to the velocity of the whole stroke. In 1939 Karpovich and Pestrecov (1939) reported their work on mathematical predictions for swimming velocity based on the assumption that the propulsive force was equal to the resistive force when velocity was constant, and that the resistive force was proportional to the velocity squared.

Although the quantitative relationships that Karpovich presented in these early reports may now be looked upon as oversimplifications of an extremely complicated subject, we must recognize and appreciate the contributions he has made in devising approaches for examining swimming performance and in stimulating continuing efforts to gain further insight into how we move in water.

Another notable in swimming research whose writings began appearing in the 1930's and continued well into the 1970's was T.K. Cureton. A dedicated advocate of physical fitness, much of his work in swimming research reflected this interest. Early reports by Cureton (1930a, 1930b) focused on the mechanical analysis of the front crawl armstroke and the crawl flutter kick. The latter investigation incorporated the use of a "kick-meter" to measure the forward propulsive force of kicking. This device, consisting of a hinged panel projected down into the water and pulled on by the swimmer, was rather primitive; however, it represents another example of ingenuity in designing an experiment to answer a question. His report on flutter kicking included a comparison of the action of the human legs with the waving movement of a fish. Fifty years later we are finding ourselves returning to such comparisons in our search for appropriate models for improving human swimming.

Over these past fifty years we may or may not be asking the same questions as our predecessors. Our ideas may not be as new as we think. The literature of the past presents findings from investigations of questions that were necessarily limited by the sophistication of the tools available at that time. The development of the electronic instrumentation we have at our disposal today has enabled us to look more critically at some of the same variables that have been examined in more primitive ways years ago. As a result, our more sophisticated and precise findings have subsequently inspired the asking of more sophisticated questions. Following are some examples of the kinds of things that are being looked at now in swimming and how researchers are going about finding answers to their questions.

One of the persistent topics that has continued to demand attention is that of swimming velocity and fluctuations within a stroke cycle. Forty years after its inception, Karpovich's Natograph was improved (Karpovich, 1970). The same idea was used, but magnetic tape was attached to the swimmer instead of line. The playback frequency of prerecorded signals on the tape indicated the swimming speed fluctuations. Further modification of the same kind of apparatus was made by Miyashita (1971). Using a pulley at each end of the pool, a nylon cord was strung between the two and attached to the swimmer's waist. The cord, pulled along by the swimmer, caused the pulley to rotate. Three holes were put in the face of one pulley to allow the passage of a light beam through to a photoelectric cell every 5 cm. The change in voltage within the photocell circuit was amplified and transmitted to a recorder. Simultaneously recorded with swimming speed was a record of the pulling and recovery cycles of both arms. He used a plastic plate with a wire strain-gauge attached to each palm. The strain-gauge device responded proportionately to the pressure applied, thus indicating when the hands were in and out of the water.

In an effort to improve on the methodology for measuring velocity fluctuations, Kent and Atha (1975) constructed a device carried by the swimmer and which left him relatively unencumbered. Their SSR, or swim speed recorder, was based on a 1949 British patent of a device that used a small impeller to respond to the flow of water passing by it. The SSR contained the impeller and a recording drum inside the cylinder strapped to the swimmer's waist. Validity and reliability checks supported its use for continuously recording swimming speed.

Craig and Pendergast (1979), used a photocell and towline device for recording velocity in their investigation of how stroke rate and distance per stroke affected swimming speed. The swimmer wore a collar attached to a fine non-elastic steel wire which passed over a two-wheeled device for recording distance every 1 cm. and velocity continuously. An observer counted the number of strokes taken over a distance by pressing a switch which registered a mark on the recorder. The results of this and subsequent works by Craig and co-workers have direct application in the teaching and coaching of swimming. They point out the importance of optimizing stroke rate, rather than maximizing it, for achieving maximum swimming velocity. The question that needs to be pursued, using these data as a starting point, is: what are the changes in stroke kinematics during the propulsive phase that lead to a decrease in velocity with an increase in stroke rate?

Cinematography has been one of the most frequently used methods for studying the kinematics of swimming performances. Both the qualitative and quantitative analyses of film records have provided insight and answers to questions we have long posed about the details of swimming movements. Until relatively recently, most of the films produced were used for qualitatively evaluating swimming performances.

Not too long ago we were forced to take measurements manually from individual film frame tracings, and the time required for analyzing the data was almost prohibitive. Within the last decade, however, image digitizers put on line with microcomputers, printers, and plotters have become available to us. The time required for data reduction and processing has been drastically reduced. Due to the three-dimensional nature of the movements performed in swimming, at least two cameras are required to quantitatively describe most of the variables we are interested in. Careful arrangement of the cameras relative to the swimmer is necessary, and some type of time synchronization of the two or three cameras is needed. A typical underwater filming situation is illustrated by Wiegand, et al. (1975). It should be pointed out here that, as the diagram depicts it, the camera-to-swimmer distance is unrealistically small to obtain a full image on film without using a wide angle lens, which produces distortion. Usually 30 to 40 feet is minimum to avoid using such a lens. This side view set-up would be matched by a front view and/or a bottom view camera for obtaining three-dimensional data.

In addition to this basic underwater filming or videotaping arrangement, a number of investigators have produced viewing apparatus specifically for their needs.

An inverse periscope was constructed by McIntyre and Hay (1975) in order to simultaneously film the overwater and underwater movements of a swimmer. Such a device gave a picture of the total stroke in a single film frame and eliminated the problem of synchronizing two film records.

Dal Monte (1971) described a movable platform he developed to film or videotape a moving swimmer. The apparatus allowed the operator, camera, and periscopic system of mirrors to move along a track on the deck at the same speed of a swimmer who could be as close as four meters away from the lens. This arrangement permits the filming of swimming movements at the same lens-to-subject angle, thereby providing more accurate records than might be obtained with a stationary camera situated a much greater distance from the swimmer.

The aquatic swim-mill reported on by Astrand and Englesson (1971) was developed to conduct physiological and biomechanical tests on swimmers without encountering pool-related problems such as variable velocity swimming and turns at the wall which interfere with any instrumentation that might be attached to the subject. This "underwater treadmill" can be likened to a flowing river in which a subject must swim to hold the same position relative to the bank. The speed of flow in the swim-mill can be changed and reproduced from 0 to 2.0 m/sec. with a great deal of accuracy. On the side of the tank is a 2.5 X 1.5 m safety-glass window for observation or fliming of the subject. The tank provides for a swimming area 4.0 m long, 2.5 m wide and 1.2 m deep. The flow is kept laminar, or smooth, by vanes at the ends of the swimming basin.

Swimming kinematics have been described also by means of electrogoniometry. Ringer and Adrian (1969) used waterproofed electrogoniometers, or elgons, to produce goniograms of the changing elbow angle during freestyle swimming. Barthels and Adrian (1971) attached elgons to the hip, knee, and ankle of swimmers performing the dolphin kick and simultaneously collected electromyographic records from the abdominal and back muscles to show the different movement patterns resulting from four different kicking conditions. Normally, elgons are used to measure joint range of motion in land activities, but they can be waterproofed with rubber balloons placed over the potentiometer and sealed with silicone sealer. The wires are then attached to a carrying pole and a recording device.

Oka, et al. (1979), also used surface electromyography in combination with electrogoniometry and cinematography to study the process of how children who could not swim without support first behaved in the water and spontaneously acquired the technique of the flutter kick. The learning process was studied periodically for three years, and the descriptions that resulted have shed light on our expectations of the development and refinement of swimming skills.

The technique of surface-electrode electromyography requires waterproofing of the electrode sites and was first used in 1964 by Ikai, Ishii, and Miyashita (1964) in analyzing swimming movements. Okamoto and Wolf (1979) used fine-wire electrodes they developed to study swimming in children and ambulation in rehabilitation patients. These in-dwelling electrodes had waterproof amplifiers close to the site of pickup and minimized recording problems. Such improvement in underwater electromyography increases the feasibility of investigating muscular activity in swimmers and in patients undergoing therapy in water. Additional encouragement for using electromyography to gain more knowledge about muscle activity during swimming is provided by Piette and Clarys (1979) who describe their successful use of telemetering the muscle potentials. Such wireless transmission of signals allows the swimmer to move more freely through the water.

Investigations dealing with forces generated by the hand are becoming increasingly popular because of the obvious significance such measures would have in optimizing swimming movements. Several approaches have been taken during the last decade, including the qualitative analyses based on observations of successful swimmers. Counsilman (1971) was probably the most influencial in popularizing the concept of lift force as a main propulsive agent in swimming. His films and diagrams call our attention to the necessity of viewing hand movements relative to the water, rather than relative to the swimmer's body, to obtain proper perspective of hand-water interaction. Barthels (1974) employed a three-dimensional film analysis of butterfly swimmers to relate the hands' apparent lift force generation to body accelerations and later proposed the ideal condition of maximizing the propulsive lift force and minimizing propulsive drag (Barthels, 1979).

Schleihauf's (1979) analysis of swimming propulsion made use of plastic resin models of the adult human hand which were immersed in flowing water in a channel. The hand models were attached to a strain-gauge apparatus for sensing and recording lift and drag forces for different finger-thumb orientations. Such techniques are based upon those used in aerodynamic and hydrodynamic research. From his data, Schleihauf was able to calculate lift and drag coefficients for various flow velocities and directions past the hand. These data were then used in combination with film records of swimmers' hands to estimate the size and direction of the lift, drag, and resultant forces used in hand propulsion. Subsequently, a coach and researcher team, Remmonds and Bartlett (1981), used full-scale models of hand and forearm shapes to study the effects of finger separation on lift and drag forces. They subjected each model to wind tunnel tests, used standard conversions to approximate water flow values, and arrived at conclusions regarding the use of the hands for propulsion.

The use of a pressure-sensitive device worn on each hand was described by van Manen and Rijken (1975). They were experimenting with its potential for evaluating the stroking movements of young swimmers in the Royal Dutch Swimming Association, Dupuis et al. (1979), also incorporated the use of a pressure transducer on the hand in a multi-instrumented study using electromyography, electrogoniometry, cinematography, and dynamography. To measure the forces on the hand during back crawl and breaststroke, a waterproofed strain-gauge pressure transducer 8 mm. in diameter was taped to a rubber glove worn by the subject. The wires from the device were attached to a carrying pole and connected to recording instruments.

Another approach to obtaining measurements from moving swimmers is described by Clarys (1979), who conducted experiments at the Netherlands Ship Model Basin. A swimmer in the water is connected by means of a girdle to a vertical rod fixed to a towing carriage which moves at controllable speeds to pull the swimmer through the water. On the carriage is carried a variety of measurement instrumentation, including strain-gauges for force measurements, recording units, and underwater television. The basin used is 200 m. long, 4 m. deep, and 4 m. wide; the carriage is capable of towing speeds up to 12 m./sec. Forces on the rod are converted to electrical signals by the strain-gauges and recorded along with towing velocity. Measurements were taken for towed swimmers and actively swimming swimmers. Resistive or propulsive forces of the swimmer were obtained by the recordings which showed whether the swimmer was being pulled by the carriage at a given speed, despite his propulsive effort, or if he was pushing the carriage. This methodology was used by Clarys in showing that the drag of actively swimming subjects was greater than the drag created by a swimmer being passively towed through the water.

Van Manen and Rijken (1975) also conducted experiments at the Netherlands Ship Model Basin. An initial study conducted by these authors was directed toward determining the contribution of propulsive force delivered by the arms or legs separately for different strokes. Their description of the use of the towing carriage apparatus for force determination was as follows:

"During measurement of the arm stroke, the swimmer who is fixed to the vertical rod by means of a girdle, stretches the legs and swims with the arms only. The carriage speed is gradually increased until it exceeds the free swimming speed. At lower speeds, a resulting forward force (thrust) is measured. When the speed is increased, the thrust decreases below zero and becomes a resistance. A similar relation is found when the swimmer stretches the arms forward and swims with the legs only." (p. 71).

Another phase of this investigation by van Manen and Rijken utilized this towing apparatus to reveal that the drag was 9 percent greater for a naked female swimmer than when she wore a slim-fitting and high close-necked swim suit (sorry, no slide available for this one).

In the presence of such a wide variety of instrumentation available today, we should be reminded upon occasion that these are merely the tools that provide us with the capability to answer thoughtful, creative questions. We must resist the temptation to collect data only because we have the instruments that permit us to do so.

The examples selected for the foregoing overview of research reflect, I think, the increasing complexity of approaches to the study of swimming. With the descriptive information we have gathered so far, the complexity of the research continues, and we see it in the works of those involved in mathematically modeling swimming movements. Real-world data are necessary for structuring such models before they can become more than simplifications of swimming mechanics. Probably the first complete mathematical analysis of human swimming mechanics was presented by Seireg and Baz (1971). Although their model assumed no flexion of the body, arms, or legs, they justified this simplification on the basis of data from literature available to them at that time. Jensen and Blanksby (1975) developed their model to account for the effect of elbow flexion and extension on the forces acting on the upper extremity segments. As more realistic data become available from continued study of swimming mechanics, we should see the modeling of swimming become increasingly useful for simulating and predicting the ideal performance for any given swimmer.

To summarize, it seems that within the last ten years we have witnessed a swimming research "boom." International symposia for all aspects of sport science are becoming more frequent and more diverse, and they provide excellent forums for dissemination of research information. More important, however, is that emphasis is being given to the sharing of information among researchers and practitioners. The current swimming journals for coaches and swimmers are very effective channels for such communication. The contents of our reports are becoming increasingly geared to stress concepts that can be readily used by the teacher and coach in learning and training situations. The importance of reporting research findings in practical terms was made even more clear to me not long ago when I handed a friend a research article on increasing force application in swimming. The response was, after a brief pause, "No wonder I can't swim, I have to know how to do square roots first!"

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