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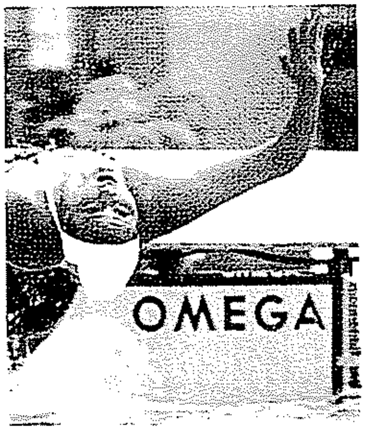
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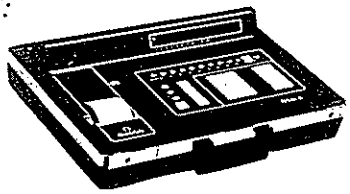


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Video-Computer Assisted Analysis of Swimming Technique

DAVID L. COSTILL, PH.D.
GARY LEE
LEO D'ACQUISTO, B.SC.
Human Performance Laboratory
Ball State University
Muncie, Indiana 47306

Abstract

The intent of this paper is to describe a video-computer system that has been designed for rapid, simple analysis of swimming technique. This system simultaneously displays a view of the swimmer's forward velocity and swimming mechanics. A real-time graph of the swimmer's velocity is superimposed on the video image of swimmer, which enables the coach and swimmer to analyze, frame-by-frame, the arm and leg actions, body position, and intracyclic timing of the stroke. Attempts have been made to illustrate the validity and application of this system for the task of improving stroke mechanics and its value in analyzing each of the competitive swimming strokes.

Introduction

It is common knowledge that technical skill is one of the major determinant of success among competitive swimmers. Unfortunately, the biomechanical differences that make one swimmer more cost efficient than another are not easily identified. With the aid of laboratory equipment we can gauge the amount of energy expended during swimming and identify those individuals who are most efficient. However, viewing the swimmers actions is only partially effective in determining which patterns of motion of "efficient" and which are "inefficient." This problem is made more difficult by the fact that we cannot relate the actions of the arms and legs to the propulsive and drag forces that act during swimming. As a result, the ability to improve swimming mechanics is limited, in part, by an inability to identify the most effective techniques, and our difficulty in changing existing "bad habits."

In an effort to provide the coach and swimming scientist with the tools to evaluate and teach optimal swimming techniques, we have developed a computer-based video system that permits the simultaneous viewing of swimming technique with a graphic display of the swimmer's forward velocity. This system enables the coach and swimmer to view, frame-by-frame, the swimmer's arm and leg actions, body position, and timing, while examining the swimmer's real-time velocity. This paper will attempt to describe this system and to illustrate its potential to improve swimming performance.

Equipment and Procedures

The components of this video-computer system are illustrated in Figure 1. The "swim-meter" used to monitor the swimmer's velocity has previously been described by Craig and Pendergast (1). It is composed of a non-elastic line that passes from a low resistance reel (less than 70 g), over an aluminum wheel with a shaft that is connected to a direct current (DC) generator (Servo Tech, Hawthorne, N.J.), to a belt worn around the waist of the swimmer. As the swimmer moves through the water the wire is pulled from the swim-meter, thereby rotating the generator wheel, producing a voltage which is propotional to the swimmer's velocity. Consequently, this swim-meter measures the hip or forward velocity of the swimmer. The voltage output from the generator is fed through a voltage divider into an analog-digital (A-D) converter and then into the computer. The output from the video camera is relayed into a series of video overlay boards (Micro-Key System, Video Associates Labs, Austin, TX).

The underwater video image of the swimmer is recorded using a standard VHS or beta camera, with a direct connection from the video output of the camera to the video input on the overlay system. The input from the A-D converter for swimming velocity is processed by software (Human Performance Laboratory, Ball State University) which creates a graphic image of the swimmer's velocity. This graph is superimposed on the video image of the swimmer, providing a synchronized display

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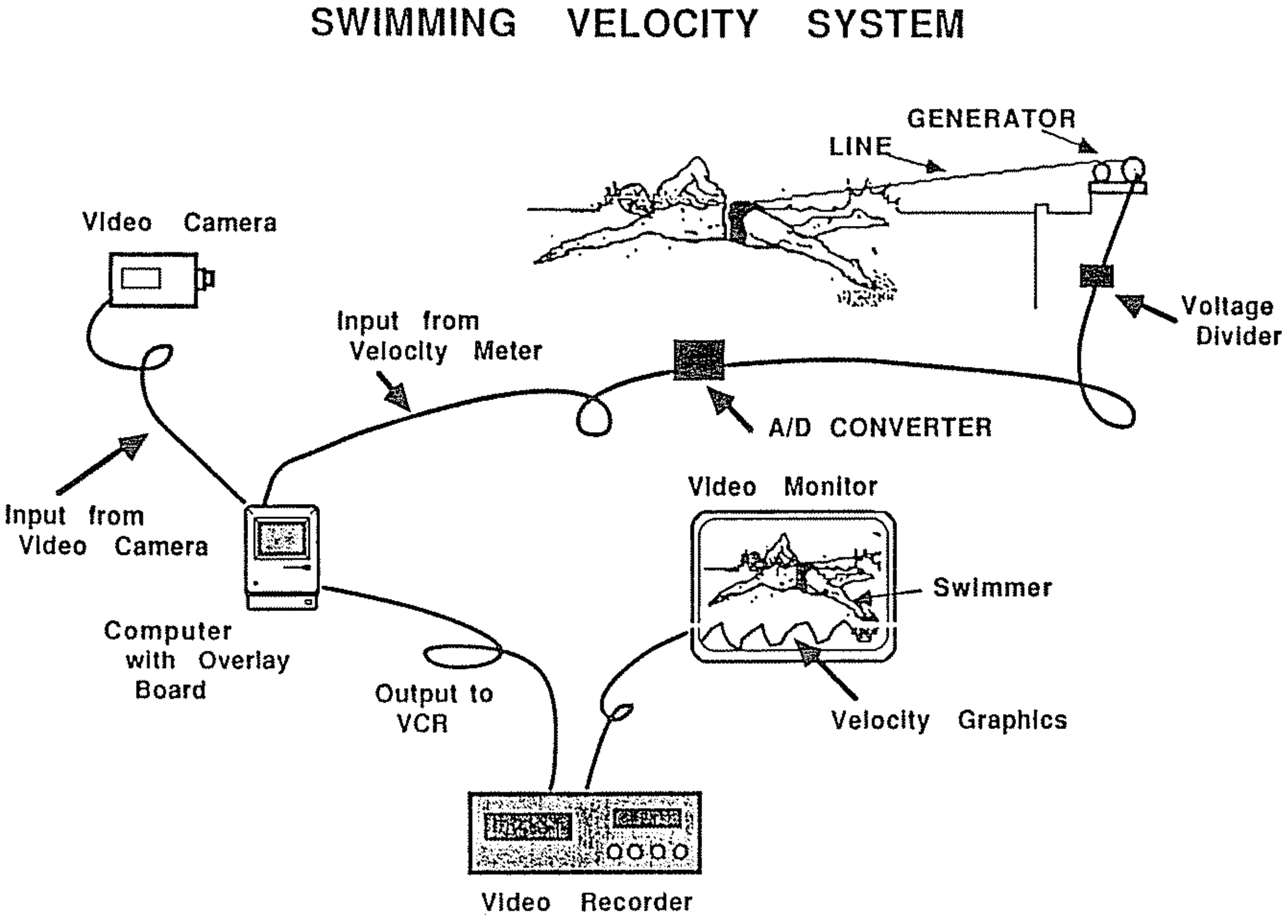

Figure 1. Design of the video-computer system used to measure swimming velocities.

of the swimmers' movements and a graphic illustration of their forward velocities. These combined images are subsequently fed to a video recorder and/or a monitor. For purposes of recording we have selected a VCR having four heads to produce high-quality images during still and frame-by-frame viewing. By replaying the recorded images it is possible to examine the swimmer's velocity at any point in the stroke cycle, and to identify which patterns of movement and body position are responsible for acceleration and decrease in velocity.

Prior calibration of the generator and graphic output enabled us to measure the swimmer's forward velocity to within 0.05 m/sec. A subroutine within this computer program also computed the mean velocity for any selected segment of the video-computer recording. In an effort to compare the forward velocity to that of the swimmer's center of mass, a swimmer was filmed, using a high speed 16 mm camera. Digitized measurements of the hip and center of mass were correlated.

System Application

The use of this system is illustrated in Figure 2. The velocity graph for a swimmer performing the breaststroke are shown in this photograph taken from the video monitor. As expected, the highest velocities during each stroke cycle were achieved during the latter stages of the kick and arm pull, with the swimmer's velocity declining markedly during the recovery of the arms and legs. Previous studies have reported similar patterns of velocity (2, 3). Figure 3, for example, shows the velocity curves for two, senior level breaststroke swimmers who are significantly different in ability. Swimmer A had a lifetime best performance of 1 min 3 sec for 100 yd (91.4 m) breaststroke, where as the other girl (swimmer B) had a best time of 1 min 12 sec for the same distance. It is interesting to note that swimmer B had higher velocities during the arm and leg actions than swimmer A, but also exhibited a greater decrease in velocity during the recovery phase of the stroke. The unique ability to maintain velocity during her arm and leg recovery enabled swimmer A to achieve a higher average velocity than swimmer B. This graphic information provides the opportunity to examine swimmer A's technique to identify the stroke characteristics that enable her to minimize the velocity changes during this recovery phase of the stroke.

This small decline in velocity during the arm and leg recovery phase is not consistently observed in the fastest

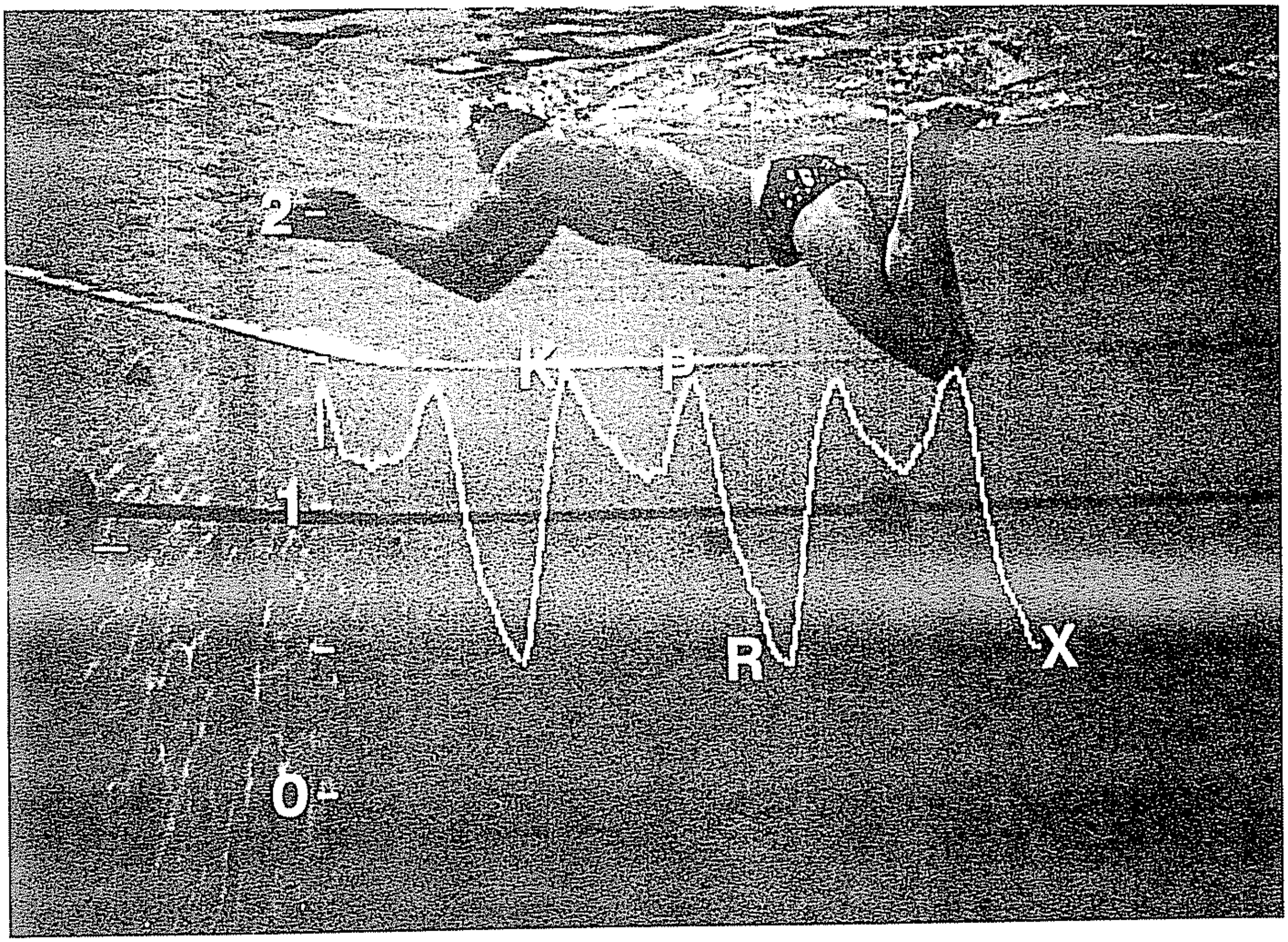

Figure 2. Illustration of the video and graphic outputs from the computer as displayed on the video monitor.

swimmers. Video recordings of U.S. National team swimmers revealed that most of the best breaststroke swimmers' velocities dropped to nearly zero during the arm and leg recovery phase of the stroke. As illustrated in Figure 4, the swimmer's peak velocities during the kick and arm pull reached values above 2.0 m/sec, some of the highest values recorded for any of the elite female swimmers. This system is also effective in assessing velocity curves in the other competitive strokes and to examine the intracyclic variations in the stroke. Figure 5 presents the graphic patterns of forward velocity for world record holders in sprint front crawl, butterfly and backstroke. Our preliminary data suggest that the peak velocities generated during the strokes are a function of muscular strength and power, whereas the mean velocity achieved during the stroke is the combined result of swimming power and the intracyclic timing of the arm and leg actions. In the breaststroke, for example, the duration of the glide between the kick and arm pull, and the time spent during the arm and leg recovery are inversely related to the swimmers mean velocity.

These individual variations in stroke velocity are also characterized by observable differences in stroke mechanics. Strengths and weaknesses in the swimmer's technique are easily associated with variations in forward velocity as measured by the video-computer system. This system provides equally valuable information for stroke analysis during front crawl, backstroke, and butterfly swimming (Figure 5).

It seems that the primary value of this technology will be to help swimmers and coaches identify stroke deficiencies and to provide immediate feedback to improve the swimmer's skill. We have initially used this technology to teach and improve breaststroke mechanics. Figure 6 shows the forward velocity curves for a masters swimmer (age 51 yr) who was studied before and after modifying his breaststroke technique. In the bottom panel of this figure (Before Modification) you will note that there is a long delay and loss in velocity between the kick and arm actions. As a consequence, the peak velocity attained during the arm pull is markedly lower than the peak attained during the kicking phase of the stroke. This delay

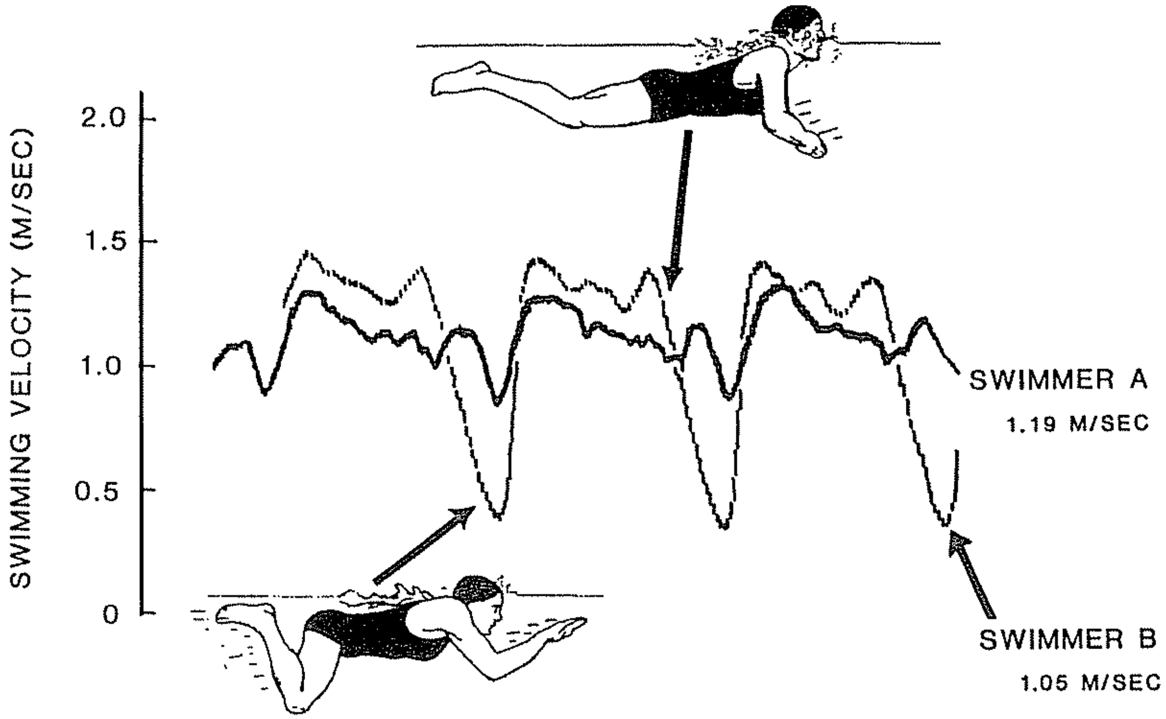

Figure 3. A comparison of the swimming velocity curves for two female breaststroke swimmers. Swimmer A had a previous best of 1 min 3 sec for 100 yd (91.4 m) breaststroke, whereas swimmer B had a best of 1 min 12 sec.

between the leg and arm actions appears to be responsible for the lower velocity achieved during the arm pull. To remedy this problem the swimmer was instructed to recover the hands forward and outward, thereby positioning the hands at the point of the catch sooner. This eliminates the delay that results when the arms are extended completely before moving from the midline to the catch position. Thus, after modifying the stroke the swimmer attained a peak velocity with the arms that was equal to or greater than that achieved during the kick. This resulted in an increase in the average stroke velocity from 0.95 m/sec (Before Modification) to 1.12 m/sec (After Modification). This change in stroke mechanics improved the swimmer's best time for 100 yd breaststroke from 1 min to 13 sec to 1 min 10.8 sec.

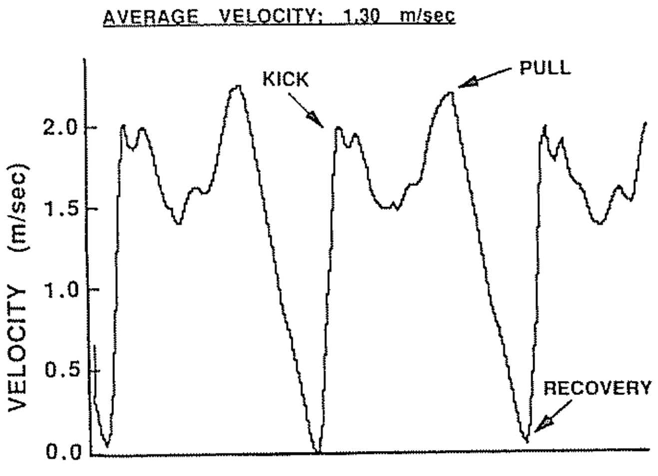

Figure 4. Graphic illustration of the velocity curve for a world class female breaststroke swimmer (J. Hau).

Some question has been raised concerning the validity of the forward velocity measurements with respect to changes in the velocity of the center of mass. Measurements of these two velocities during front crawl and backstroke swimming revealed no significant differences during any phase of the stroke cycles. There are, however, phases of the breast and butterfly strokes that show significant differences in the velocities of the hip and center of mass. In breaststroke, for example, the forward and rearward movements of the arms and legs cause some variation in the forward and center of mass velocities, which are illustrated in Figure 7. The resultant correlation between these two velocities during one complete breaststroke cycle was 0.80. From a practical point of view, however, these differences are of little value to the coach and swimmer who are concerned primarily with the interpretation of the actions of the arms and legs in gross forward movement of the body.

At present we are attempting to validate the video-computer velocity measurements by comparing intracyclic variations with swimming efficiency (i.e. oxygen uptake) and distance per stroke. This information will enable us to determine which velocity patterns and cyclic rhythms are most effective.

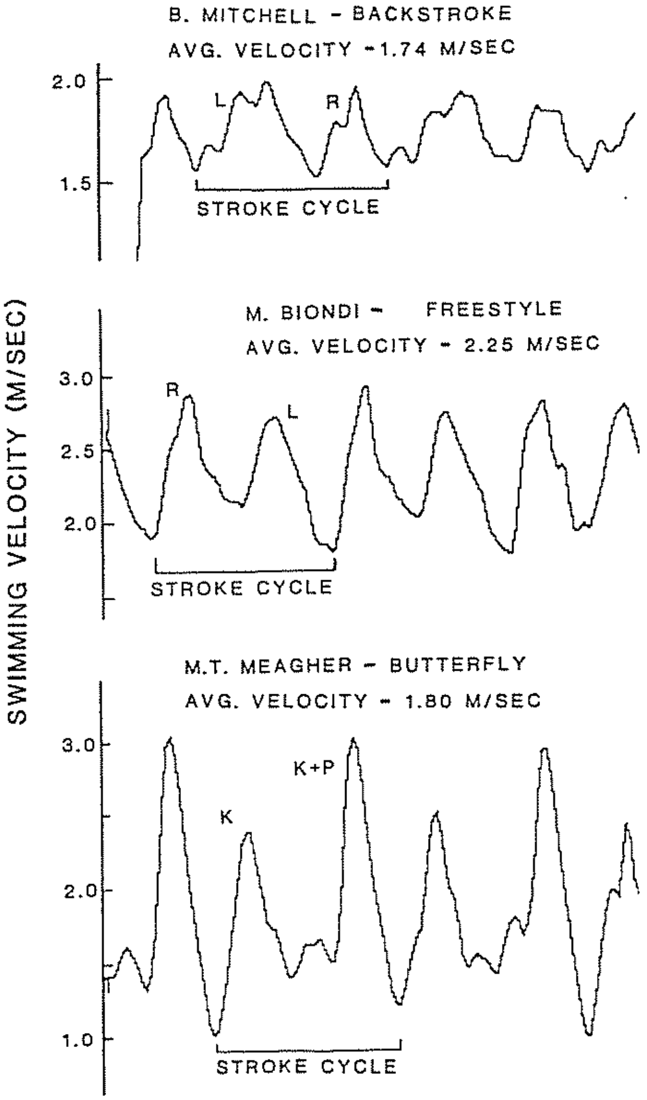

Figure 5. Graphic illustration of the velocity curves for three world class swimmers.

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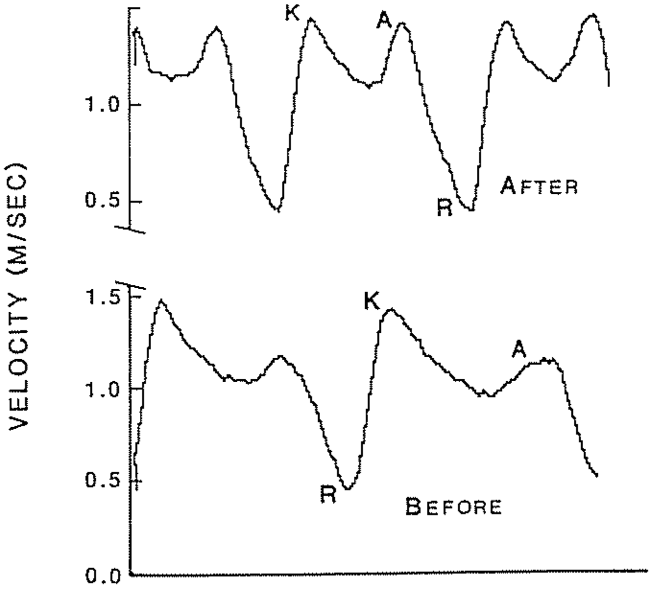

Figure 6. Before and after technique modification in the breaststroke for a masters swimmer. Peak values during the kick and arm pull phases of the stroke are noted as "K" and "A", respectively. The drop in velocity during the arm and leg recovery is identified by "R".

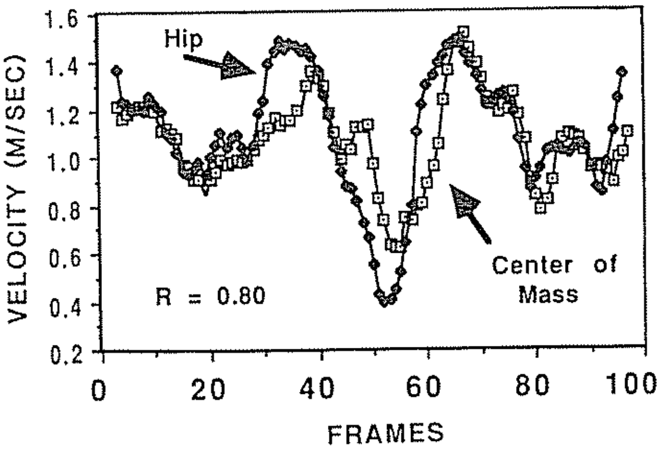

Figure 7. Measurements of hip and center of mass velocity during breaststroke swimming.

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The Relationship Between the Forward Velocity of the Center of Gravity and the Forward Velocity of the Hip in the Four Competitive Strokes

CHERYL W. MAGLISCHO, ED.D.
Dept. of Physical Education
California State University, Chico
Chico, California 95926

ERNEST W. MAGLISCHO, PH.D.
Athletic Dept.
California State College, Bakersfield
Bakersfield, California 93309

T.R. SANTOS, B.S
Dept. of Physical Education
California State University, Chico
Chico, California 95926

Abstract

The purpose of the study was to determine the relationship between the forward velocity of the hip and the forward velocity of the center of gravity. Eighteen members of the 1984 Olympic Swimming Team were filmed from underneath at 64 frames per second while performing the four competitive strokes at race pace. Every second frame of one complete stroke cycle was digitized. One film trail was digitized ten times to determine the reliability of the digitizing procedures. Velocity curves for the hip and center of gravity were analyzed and Product-moment correltions calculated to determine the relationship between the two variables. Critical ratios were calculated to determine significant diffeences between the reliability coefficients and the r's for the hip and center of gravity velocities. Reliability coefficients ranged from .89 to .96, with an average of .91. Significant relationships existed between the velocities of the hip and center of gravity for the breaststrokers (.81 to .90), butterflyers (.91 to .98), freestylers (.86 to .96), and for nine of ten backstrokers (.63 to .94). Critical ratio tests were insignificant for all but five backstroke swimmers. These results warranted the following conclusions: 1) the forward velocity of the hip can be used as a tool for diagnosing problems within stroke cycles, 2) the center of the body at the hip rather than the side of the hip should be used in these studies, and 3) hip velocity is not an accurate measure of true swimming velocity.

Introduction

Researchers and coaches are constantly searching for more accurate methods to diagnose the propulsive efficiency of competitive swimmers. At present the most accurate method involves plotting the forward velocities of swimmers' centers of gravity. A coach or researcher can feel confident that a swimmer is losing propulsive force during a certain phase of his/her stroke when these curves exhibit either large decelerations of forward velocity or when accelerations of forward velocity are not as great as would be expected. Unfortunately, plotting the center of gravity is complex and time consuming. Because of this, the interval between data collection and communication of results to the swimmers is several hours. These long delays reduce the effectiveness of communication.

Miyashita (10) presented a simplified method for diagnosing propulsive efficiency in 1970. It was based on measuring fluctuations in the forward velocity of the hip when swimmers were partially tethered to a recording device. Since the center of gravity is located in the hip region, it was suggested that the forward movements of swimmers' hips might provide an estimate of fluctuations in forward velocity that is accurate enough for diagnostic purposes. The advantage of using the hip for diagnostic purposes is obvious. If the forward velocity of the swim-

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mers' hips and the forward velocity of their centers of gravity showed a high relationship, it would be necessary to digitize only one landmark instead of the twenty-one landmarks generally required to calculate the position of the center of gravity. As a result, the interval of time between data collection and communication of the results would be greatly reduced. Unfortunately, the relationship between the forward velocity of the hip and center of gravity has never been determined for competitive swimmers.

There is a great need for a less complicated and less time-consuming method to help in evaluating stroke efficiency. If a method could be devised to simplify the process of calculating forward velocity, the coach, swimmer, or researcher would have the ability to detect and evaluate decreases in propulsive efficiency in a more practical and efficient manner. With a simplifed method, the coach could monitor the swimmer's stroke mechanics on a more frequent basis. This would assure constant and proper modification of the swimmer's stroke defects. In addition, deficient stroke mechanics that would otherwise go unchanged or undetected could not be evaluated and corrected. Therefore, the purpose of this study was to determine the relationship between swimmers' forward hip velocity and the forward velocity of their centers of gravity during one stroke cycle.

Methodology

The investigation was limited to analyses of the four competitive strokes (butterfly, backstroke, breaststroke, and freestyle) performed by eighteen male and female members of the 1984 United States Olympic Swimming Team. The ages of the subjects ranged from seventeen to twenty-four years.

All testing took place at the Mission Viejo Swimming Center of June 12, 1984, two weeks prior to the 1984 Olympic Games. The pool was a regulation fifty meters by twenty five yards with a depth from six to twelve feet. A Redlake Locam 16mm, DC motor driven movie camera was placed in a plastic underwater housing and interfaced to a switch box that could be operated from the pool deck. The camera was secured by weights to the bottom of the pool twelve feet below the surface. It was leveled and positioned so that it faced directly up. The film speed was set at sixty-four frames per second.

Each subject swam the length of the pool at competition speeds, passing directly over the camera in the process. A stop watch was used to insure proper speed. The trial was repeated if not swum at the correct speed. Each swimmer performed at least three trials using his/her specialty stroke. Filming began just before the swimmer passed directly over the camera to insure a complete view of the stroke.

Acceptable trials for analysis were those in which the entire body could be viewed throughout a complete stroke cycle. Ten trials were selected for each stroke. A total of forty trials were analyzed in all.

The selected trials were projected by an Eki Motion Analyzer on a smooth white paper fastened to a wall. A vertically suspended Numonics digitizer interfaced to the California State University Chico computer was used to collect data. One complete stroke cycle was digitized for each subject in the butterfly and breaststroke trials. One complete underwater stroke of either the right or left arm was digitized for each subject in the freestyle and backstroke trials. For butterflyers, digitizing commenced as the swimmers' hands were seen entering the water to begin a stroke cycle and continued until the hands were seen entering the water to begin the next cycle. In breaststroke, digitizing commenced when the swimmers' hands began separating to start the propulsive phases of the armstroke and continued until the arms returned to the same position to begin the next stroke cycle. For freestyle and backstroke, digitizing commenced when the hand was seen entering the water to begin an underwater armstroke and continued until that hand left the water. Every second frame was digitized. The position of twenty segmental endpoints and a reference point were determined in each digitized frame. The points selected for analysis were digitized in the following order: 1) tip of right middle finger, 2) right wrist, 3) right elbow, 4) acromion process of right shoulder, 5) acromion process of left shoulder, 6) left elbow, 7) left wrist, 8) tip of left middle finger, 9) tip of right big toe, 10) right ankle, 11) right knee, 12) right hip, 13) left hip, 14) left knee, 15) left ankle, 16) tip of left big toe, 17) right ear, 18) sternum, 19) crotch, 20) top of head, 21) and reference point.

The digitized data was then analyzed by the computer program JFILMB. This program calculated the position of the center of gravity of the body as well as the velocities of that point and each of the twenty-one points required for the center of gravity calculation. Center of gravity calculations were based on Dempster's data (1).

A film trial for one swimmer was digitized ten times in order to determine the reliability of the digitizing process. Reliability was established by correlating the forward velocity of the center of gravity on the first trial with the velocity patterns of the center of gravity for the additional nine trials.

The forward velocity curves for the hip and center of gravity for each subject were then graphed to illustrate the relationship between the two in each of the four competitive strokes. The forward velocity of the swimmers' crotch, rather than the hip, was used in the backstroke and freestyle graphs when it was determined that digitizing the outer portion of one hip introduced error into these relationships. Graphs were examined to determine at which points during the stroke cycles the two velocities differed. Product moment correlation coefficients were also calculated between the two variables for each subject. These were interpreted at the .01 level of significance.

Critical ratios were calculated to determine if significant differences existed between the reliability coefficients and the coefficients calculated for the hip and center of gravity. The correlation coefficients were first converted to Fisher's Z functions. The significance of the difference between the Z's was then determined. A critical ratio of 2.54 was significant at the .01 level and a critical ratio of 1.96 was significant at the .05 level.

Findings

Reliability of Digitizing Procedures

Table 1 includes the reliability coefficients determined from digitizing the same trial of a subject's freestyle ten times. The velocity of the center of gravity during one underwater armstroke was calculated for each of the ten sets of digitized data. The velocity curve from the first digitized trial was then correlated with each of the nine subsequent trials. These correlations ranged from .89 to .96 with the average being .91. All of the coefficients were significant beyond the .01 level of confidence.

Relationship Between the Forward Velocity of the Hip and the Forward Velocity of the Center of Gravity in the Breaststroke

Table 2 contains a summary of the relationship between the forward velocity of the center of gravity and the forward velocity of the hip for each of the ten breaststroke swimmers. These correlations ranged from .81 to .90. The average was .87. All of these coefficients were significant beyond the .01 level of confidence.

An important finding in these comparisons and comparisons within other competitive strokes was that accelerations and decelerations of the hip velocity closely paralleled those of the center of gravity in all phases of the stroke cycle. In no case did one decelerate when the other was accelerating and vice versa. It is also important to note, however, that these fluctuations did not produce identical velocities nor did they occur at exactly the same moments in the stroke cycles. These similarities and differences are illustrated by the graph in Figure 1 and are described in the following paragraphs.

Table 1. Reliability Coefficients for Digitizing One Trial Ten Times.

Trials	Correlation Coefficient
1 vs. 2	.90*
1 vs. 3	.92*
1 vs. 4	.90*
1 vs. 5	.90*
1 vs. 6	.89*
1 vs. 7	.93*
1 vs. 8	.90*
1 vs. 9	.96*
1 vs. 10	.91*

* Significant at the .01 level of confidence

Table 2. Correlation Coefficients for Hip and Center of Gravity Velocities For Breaststroke Swimmers

Subject	Number of Points	Correlation
1	34	.90*
2	31	.89*
3	34	.85*
4	43	.81*
5	44	.89*
6	34	.89*
7	31	.89*
8	39	.87*
9	42	.87*
10	38	.88*

* Significant at the .01 level of confidence

The velocities of both the hip and center of gravity accelerated during the propulsive phases of the armstroke. The velocity of the hip tended to accelerate more rapidly and reached a higher velocity during this phase. Velocity peaks for the hip also developed slightly before those of the center of gravity during this phase of the armstroke.

Both the hip and the center of gravity showed a large decrease in velocity during the recovery of the arms and legs. However, the center of gravity decelerated less than the hip. In addition, the deceleration was more gradual with the lowest velocity reached slightly after it was reached by the hip.

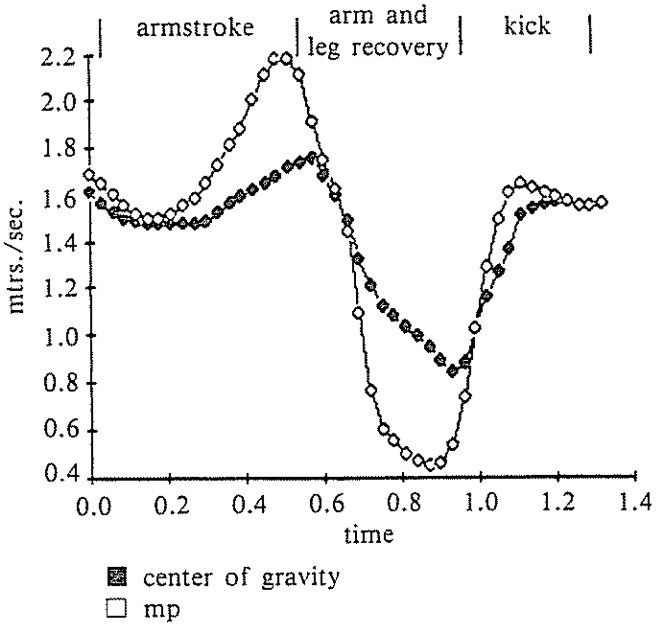

Figure 1. Typical velocity graph for a breakstroke swimmer.

Table 3. Correlation Coefficients for Hip and Center of Grafity Velocities For Butterfly Swimmers

Subject	Number of Points	Correlation
1	24	.92*
2	24	.98*
3	23	.94*
4	25	.97*
5	33	.95*
6	28	.93*
7	34	.98*
8	28	.97*
9	25	.92*
10	27	.91*

* Significant at the .01 level of confidence

During the outsweep of the kick the velocity of the hip accelerated more rapidly and to a greater value than the velocity of the center of gravity. Both the hip and center of gravity decelerated to nearly the same velocity during the insweep of the kick and remained approximately equal until the beginning of the next stroke cycle.

Relationship Between the Forward Velocity of the Hip and the Forward Velocity of the Center of Gravity in the Butterfly

A summary of the correlation coefficients which indicate the relationship between the forward velocity of the center of gravity and the forward velocity of the hip for the ten butterfly swimmers appears in Table 3. The correlation coefficients ranged from .91 to .98. The average was .95. All of the coefficients were significant beyond the .01 level of confidence.

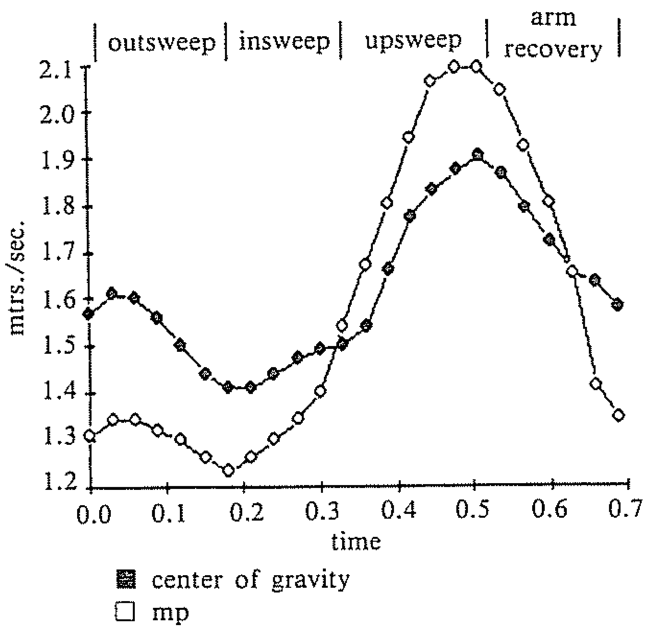

Figure 2. Typical velocity graph for a butterfly swimmer.

Once again, accelerations and decelerations of forward hip velocity and the forward velocity of the center of gravity paralleled one another in all of the subjects studied. However, as in the breaststroke, there were differences in the rates of fluctuation of the hips and centers of gravity as well as differences in the values attained by the two measures of forward velocity. The graph depicted in Figure 2 is representative of the similarities and differences observed among the subjects in this stroke.

Both the hip and center of gravity accelerated during the arm entry and downbeat of the first kick. This was followed by a deceleration of both during the outsweep portion of the armstroke. Although the patterns of the curves were similar, the forward velocity of the center of gravity was higher than the forward velocity of the hip during this phrase of the armstroke.

During the insweep and upsweep, both the center of gravity and hip accelerated markedly for all subjects. During the insweep the center of gravity tended to accelerate somewhat more rapidly than the hip. The reverse was true during the upsweep, with the velocity of the hip accelerating more rapidly and reaching a greater peak velocity than the center of gravity.

The forward velocities of both the hip and center of gravity decelerated during the arm recovery. The hip generally decelerated more rapidly than the center of gravity and reached a lower velocity.

Relationship Between the Forward Velocity of the Hip and The Forward Velocity of the Center of Gravity in the Freestyle

The correlation coefficients which show the relationship between the forward velocity of the hip and the forward velocity of the center of gravity for freestyle swimmers appear in Table 4. These relationships ranged from .86 to .96. The average coefficient was .87. All of these coefficients achieved a level of significance beyond .01.

The velocity curves for both the hip and center of gravity showed similar patterns of acceleration and decelera-

Table 4. Correlation Coefficients for Hip and Center of Gravity Velocities for Freestyle Swimmers

Subject	Number of Points	Correlation
1	25	.90*
2	20	.86*
3	22	.88*
4	25	.88*
5	26	.96*
6	24	.90*
7	24	.86*
8	27	.87*
9	27	.85*
10	20	.88*

* Significant at the .01 level of confidence

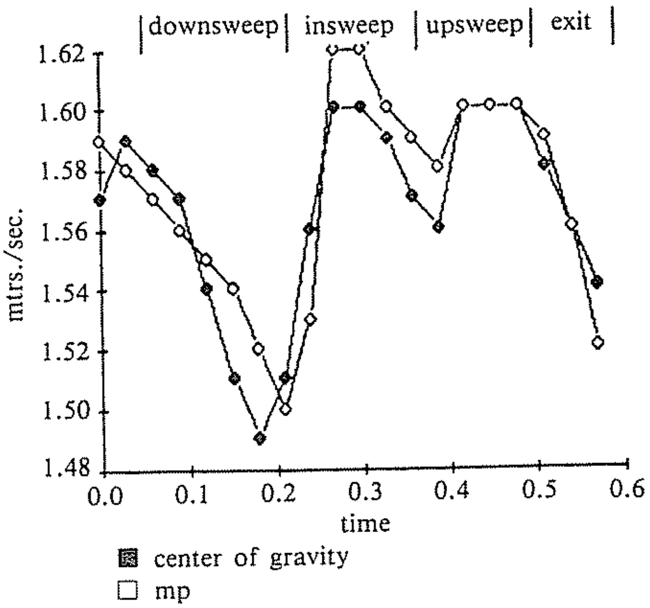

Figure 3. Typical velocity graph for a freestyle swimmer.

tion for nine of the ten subjects. The graph in Figure 3 is typical of the velocity patterns exhibited by those subjects.

Both the hip and center of gravity decelerated for all subjects during the downsweep of the freestyle. The hip decelerated much more rapidly and reached a lower velocity than did the center of gravity. Both the hip and center of gravity accelerated during the insweep that followed.

Both the hip and center of gravity accelerated during the upsweep portion of the stroke. The hip generally reached a slightly higher peak velocity than that reached by the center of gravity. Both the center of gravity and the hip decelerated as the subjects hands exited from the water.

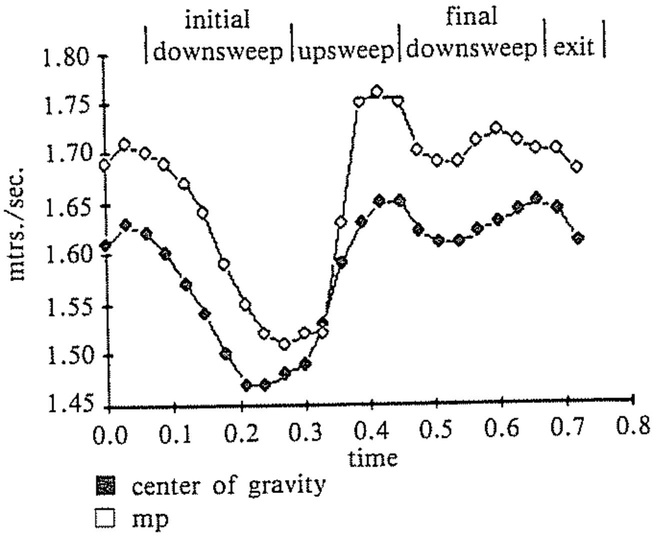

Figure 4. Typical velocity graph for a backstroke swimmer.

Table 5. Correlation Coefficients for Hip and Center of Gravity Velocities For Backstroke Swimmers

Subject	Number of Points	Correlation
1	23	.87*
2	22	.67*@
3	25	.94*
4	22	.66*@
5	27	.82*
6	22	.63*@
7	20	.75*
8	19	.64*@
9	22	.03 @
10	23	.85*

* Significant at the .01 level of confidence
@ Significantly different from reliability coefficients

As indicated previously, one subject did not follow the typical pattern. In that case, the forward velocity of the center of gravity accelerated during the insweep of the armstroke while the forward velocity of the hip decelerated. This subject followed the same pattern as the other nine swimmers during the upsweep and exit.

Relationship Between the Forward Velocity of the Hip and the Forward Velocity of the Center of Gravity in the Backstroke

The relationships between the forward velocity patterns of the hip and center of gravity for each of the ten backstroke swimmers appear in Table 5. The correlation coefficients ranged from .03 to .94. The average relationship was .69, with all but one correlation being greater than .63. All of the coefficients except the .03 were significant beyond the .01 level of confidence.

The greatest number of differences in the forward velocity curves of the hip and center of gravity were observed in this stroke. Fluctuations paralleled one another in only 6 of 10 subjects.

The graph in Figure 4 shows a typical velocity pattern for the hip and center of gravity for the six subjects. Both the hip and center of gravity decelerated during the entry and initial downsweep. The hip and center of gravity accelerated during the upsweep portion of the arm stroke. The hip generally reached a greater peak velocity than did the center of gravity. The velocities of both the hip and center of gravity decelerated slightly during the transition from the upsweep to the final downsweep. This was followed by an acceleration of both the hip and center of gravity. The hip generally reached a higher velocity than the center of gravity. The velocity of both the hip and the center of gravity decelerated as the swimmers' hands left the water.

The remaining four subjects followed the pattern depicted in Figure 4 during the initial downsweep and upsweep portions of the underwater armstroke. However, certain differences were observed during the final downsweep of the armstroke. In three subjects the hip accelerated while the center of gravity decelerated just after the final downsweep was completed and the swimmers were bringing their hands toward the surface. The reverse occurred with the fourth swimmer. The center of gravity accelerated while the hip decelerated during the middle of the final downsweep.

Discussion

In the first portion of this study the reliability of the digitizing process was compared to the correlations between the hip and center of gravity. The digitizing process required that the authors manually determine the location of various body parts. This was not an easy process. Water turbulence and lack of clarity in underwater motion pictures versus films taken on land made those body parts difficult to locate. Thus, a certain amount of error was inherent in the human digitizing process. Therefore, it was important to determine the reliability of this process before comparing the forward velocities of the swimmers' centers of gravity to the forward velocities of their hips. This was done by digitizing the same trial ten times and calculating correlation coefficients for the relationship between the velocity of the center of gravity of the first trial and each subsequent trial. It was assumed that correlation coefficients between velocity curves for the hip and center of gravity which were significantly lower than those established from digitizing one trial ten times would indicate a lack of agreement between the two measures of forward velocity.

Results indicated that, for three of the four competitive strokes, the reliability coefficients were not significantly different from the coefficients for the velocity curves of the hip and center of gravity. Those strokes were the breaststroke, butterfly and freestyle. The only differences were noted among the backstroke subjects. Even in that group, there were no significant differences between the reliability coefficients and the correlation coefficients for the hip and center of gravity for five of the ten subjects. Of the remaining five, four were significantly different at the .05 level while the coefficient for the tenth subject was significantly different at the .01 level.

The reason that coefficients for five of the ten backstroke swimmers were significantly different from the reliability coefficients is probably due to difficulties encountered when digitizing subjects in this stroke. There is usually more turbulence around backstrokers' bodies than is present among swimmers in the other strokes. These five cases do not negate the usefulness of forward hip velocity for diagnosing stroke mechanics. It is reiterated that 35 of the 40 trials for all competitive strokes were not significantly different from the reliability measures. In addition, the correlation coefficients between velocity curves for the hip and center of gravity were significant for nine of the ten backstroke swimmers studied.

Fluctuations in the forward velocity curves of the hip and center of gravity were compared in the second part of this study. A high positive relationship was found in 39 of 40 comparisons. In addition, both usually followed similar patterns of acceleration and deceleration during the stroke cycle in all four competitive strokes. This was true in 34 of 40 subjects studied. Four of the six subjects who did not show similar patterns of velocity fluctuation between the hip and center of gravity were backstrokers. Of the remaining two cases one occurred among the ten subjects in the butterfly and the other among the ten subjects in the freestyle. There were no fluctuation differences noted among the ten breaststrokers.

It is also important to point out that when differences in the directions of these fluctuations occurred they were never evident in more than one phase of the armstroke. This small number of differences probably represented human error in the digitizing process rather than actual differences in the velocity patterns of the hip and center of gravity for these subjects.

Coaches who intend to use this method should be aware that there are limitations to using the hip as a measure of forward velocity. The values will not accurately reflect the swimmers' true velocity. Although the hip and center of gravity followed similar patterns of acceleration and deceleration, the values reached were different during most phases of the stroke cycle. The coach must be careful to compare only hip velocities when attempting to determine when the *amounts* of acceleration or deceleration represent a problem within a stroke cycle. For example, if the hip velocity of one breaststroke swimmer was compared to the velocity of the center of gravity of another the coach might mistakenly assume that the former swimmer had a more propulsive armstroke than the latter. More importantly, the coach might mistakenly conclude that the former swimmer was decelerating too rapidly during the arm and leg recovery. This could, perhaps, cause the coach to miss a real stroke problem in the armstroke of the former swimmer while attempting to correct a problem in the recovery that did not exist.

The authors would like to mention one additional source of error that could occur when using the hip as a diagnostic tool. The velocity patterns of the hip and the center of gravity will exhibit greater differences if the lateral side of the hip, rather than the center of the body at the hip, is used as a landmark when studying the freestyle and backstroke. That source of error was discovered by accident during the course of this study. Intially, the side of the hip closest to the camera was used to calculate hip velocity. Using this procedure, all 10 subjets in the backstroke portion of this study exhibited correlation coefficients between the velocity of the hip and center of gravity that were lower than .77. Most were in the range of .20 to .60. The results were not quite so divergent in the freestyle. Nevertheless, five of the subjects had coefficients that were below .80. It was theorized that the low coefficients in these two strokes might result from swimmers coming out of alignment during certain portions of the stroke cycle, forcing the side of the hip that was being digitized forward or backward relative to the other side. It is well known that the lateral alignment of swimmers is easily distrubed in the freestyle and backstroke where alternating arm motions are used. It was decided, therefore, to plot the forward velocity of the crotch and compare that to the forward velocity of the center of gravity in these two strokes. This was done because the location of the crotch most closely approximated the center of the hip and would be less inclined to be pulled out of alignment by the alternating action of the arms.

When these two were compared the coefficients for freestyle swimmers improved markedly with none calculated to be lower than .86. The coefficients for backstroke swimmers also improved with only one lower than .63. These results together with inaccuracies inherent in the digitizing process suggest that a measuring device attached to the swimmers's hips or to some other part of the trunk might be a more accurate method for diagnosing stroke defects. This device should not restrict swimming speed since it has been shown that tethered and partially tethered swimming cause athletes to change their stroke mechanics (7).

Conclusions

The results of this study warrant the following conclusions:

1. The forward velocity of the hip can be used as a tool for diagnosing problems within stroke cycles because the velocities of the hip and center of gravity follow similar patterns in the four competitive strokes. The relationship is very high in the breaststroke, butterfly and freestyle. The relationship in the backstroke is also good although it is not as high as in the other strokes.

2. Hip velocity is not an accurate measure of true swimming velocity. Although the hip and center of gravity tended to accelerate and decelerate at nearly the same time, the center of gravity, which is accepted as an accurate measure of swimming velocity, tends to reach different values at various points in the stroke cycle.

3. The center of the body at the hip, rather than the side of the hip, should be used to calculate velocity when digitizing is used to measure fluctuations within a freestyle or backstroke cycle. In strokes where the arms move alternately, the side of the hip may be pulled out of alignment by the arm movements and appear to be accelerating or decelerating more so than the center of the body.

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Relationship of Maximum Sprint Speed and Maximal Stroking Force in Swimming

Carol L. Christensen, Ph.D., FACSM
Gordon W. Smith
San Jose State University
Department of Human Performance
San Jose, California 95192

In striving to produce excellence, swim coaches have employed many different methods of testing, ranging from general strength tests to specific in-water tests. In recent years tests that simulate swimming motions such as the dry-land Biokinetic Swim Bench have been used. This type of test is advantageous because, to some extent, it simulates the freestyle motion. Sharp and colleagues (7) agreed that, while it does simulate the freestyle motion, it does not exactly mimic the pull during freestyle swimming. One of the weaknesses of this type of testing is that the Biokinetic Swim Bench measures only arm and shoulder girdle strength and excludes any contribution made by the legs. It also fails to measure any lateral or vertical stroking movements nor are test results influenced by other factors important in swimming such as body position and swim technique.

The most specific form of testing in swimming is tethered swimming. Montpetit (4) and Hopper, Hadley, and Bambauer (2) found that tethered swimming and free swimming were not markedly different; except that the load placed on the upper extremities in tethered swimming was much greater than during free swimming. The biggest advantage of this type of testing is believed to be its specificity to actual freestyle stroke mechanics. Hopper, et al. (2) showed a correlation between dry-land testing and sprint speed of $r = -.71$ while "in-water testing" (tethered swimming) showed a higher correlation of $r = -.85$ with sprint speed. Costill, King, Holdren, and Hargreaves (1) reported similar findings; that is, a poorer correlation between dry-land tests associated with the Biokinetic Swim Bench and sprint performance ($r = .62$) than between a power swim and sprint performance ($r = .84$). These results suggest that it is possible for moderately or poorly skilled swimmers to score high in dry-land testing but not during in-water testing, indicating lower specificity of dry-land testing. Montpetit (4) agreed with this and suggested that swimmers might best train for power by using specific exercises that take advantage of proper stroke mechanics in the water. Sharp and Costill (6) further suggest that coaches should be interested in "measuring and training force capability during a dynamic action that most closely copies the movement of actual swimming" (p.42).

Many swim distances have been examined for their relationship with sprint performance, but most studies have utilized distances of 50 meters or more to measure sprint speed (2,4,5). At these distances, times are greater than 20 to 30 seconds and may reflect average velocity rather than maximum swim velocity.

The Purpose of the Study

The review of the literature suggested a study was needed to compare a tethered swimming test of stroking force with a test of maximum sprint speed at a distance where maximum speed was more likely to be attained and maintained. The purpose of this study was to examine the relationship of maximum stroking force exerted by an individual during tethered swimming and speed attained during a 25-yard freestyle sprint.

Method

Subjects for this study consisted of 39 competitive swimmers who were members of an aquatic club; 24 male and 15 female members of the senior swim group volunteered to participate in this study. They ranged in age from 14 to 20 years. They were asked to participate only in their normal training program while the study was being conducted. Informed consents were obtained from each subject prior to initiation of the experiment.

Maximum voluntary stroking force (MSF) was measured with the Hencken Digiswim Swim Guage. A memory switch was installed in the apparatus so that the highest force the swimmer produced during the test was recorded. The swimmer was placed in the water in a horizontal postion perpendicular to the side of the pool with a leather or velcro harness fastened at the waist and attached to a cable. The other end of the cable was attached to the swim guage which was connected to the pool side so that force was exerted at a 90 degree angle to the pool side and the cable was parallel with the water. The swimmer then swam away from the guage and the force that she/he applied to the cable registered on the readout of a strain guage. The Caldwell test regimen used in this study has been used previously as a procedure to measure maximum stroking force in the water (3,4). In this regimen, after a build-up phase of no more than 2 seconds, the subject was required to maintain a steady maximal exertion for at least 3 seconds. The highest force was recorded as the subject's score. Each subject performed two practice trials to assure familiarity with the test procedure and equipment. These trials were followed by two experimental trials in which maximum force was measured. If the results of these two trials showed a difference of less than 5%, the higher of the two scores was accepted as the MSF. If, however, the difference between the two trials was greater than 5%, a third trial was taken and the higher of the two trials with less than 5% difference was considered MSF. Each subject was give no less than 2 minutes rest between trials.

To measure maximal sprint speed (MSS) each subject swam two 25-yard freestyle sprints as fast as possible. The subject began with an in-water start and was timed by three skilled testers using stopwatches that were capable of timing to .01 of a second. The watches were started at the instant the subject's feet broke contact with the wall and were stopped when her/his hand touched at the finish (7). If the difference between the first two sprints was greater than 5%, a third trial was given; the higher of the two trials with less than 5% difference was considered MSS. Each subject rested for at least 2 minutes between each sprint; this allowed sufficient rest to support a second maximal effort.

There were no less than 4, and no more than 7, days between MSF and MSS tests. All subjects warmed up prior to each of the test conditions and were given standard verbal instructions on how to perform each test. Pearson Product Moment Correlations were used to determine the relationship beween MSF and MSS. Two *t*-tests were performed to determine if there were significant differences between men and women with regard to MSF and MSS.

Results

The results of this study are reported in Table 1. Significant correlations were noted between MSF and MSS for males ($r = -0.685$, $p < .005$) and for females ($r = -0.576, p < .01$). Significant differences between men and women for MSF ($t = 6.67, p < .001$) and MSS ($t = 8.62$, $p < .01$) were also noted.

Table 1

Pearson Product Moment Correlation Coefficient (r) between Maximum Voluntary Force (MSF) and Maximum 25-yard Freestyle Sprint Speed (MSS)

		MSF (lbs)		**MSS (sec)**		**r**	**p**
Men	24	79.3	(12.6)	11.43	(.48)	−0.685	<.005
Women	15	54.9	(8.0)	12.78	(.48)	−0.576	<.01

Discussion

The data of our study supports that of previous studies (1,2,4), suggesting that sprint speed is related to the stroking force a swimmer can generate. This information may prove helpful to swim coaches. Using a test of power or maximum stroking force a coach could gather data indicating whether an individual would be a promising sprinter. The significant correlation between MSF and MSS also suggests that, to improve an individual's maximum sprint speed, she/he must improve maximum stroking force.

The significant negative correlations between MSF and MSS for both males and females suggest that, while there may not be a cause and effect relationship, testing MSF could be used to assess training changes. In a study by Montpetit (4), MSF was tested and compared to swimming performance at various distances. The correlations between MSF and a maximal effort 50 meter swim were found to range from −.61 to −.78 (coefficients were different for various age groups). For a 100 meter swim, relationships of $r = -.50$ to $-.77$ were found and for distances of 200 meters correlations ranged from −.35 to −.75. In almost all cases lower correlations were from younger siwmmers while higher correlations came from older elite swimmers. Costill, et al. (1) and Hopper, et al. (2) reported stronger correlations between sprint performance and force generated during tethered swimming than the present study. Differences may have been due to age differences of subjects and/or differences in the method employed to measure MSF.

In this study, and Miyashita and Kanchisa (5), a difference existed between men's and women's test scores for both MSF and MSS, with men's scores being consistantly higher than women's. This was to be expected since young adult males tend to be larger and usually have more muscle mass, and therefore strength, than females of similar age. These differences would provide the males with more muscle and strength for stronger stroking and could account for the higher correlation ($r = -.85$) between MSS and MSF for the total sample.

Our results, combined with the results of others (1,2,4), suggest that in-water testing may be a valuable tool for coaching swimmers. The correlational evidence available suggests that this might be more valuable than testing on a Biokinetic Swim Bench since it allows for the measurement of maximum or peak forces generated when using the entire stroke (pulling and kicking) rather than being limited to measuring forces generated by arms only. It also allows the coach to measure the parts of the stroke, pulling or kicking, separately if desired. When initial expense is considered, the desirability of tethered swimming may be enhanced.

Before either type of testing (dry-land or tethered) can be used for accurate predictions more testing needs to be completed, norms need to be established, and guidelines determined for assessing sprinters and distance swimmers. In the meantime, a tethered swimming test for MSF may be used to evaluate, monitor, and adjust training programs (i.e., improved MSF might indicate improved stroking force and a need to adjust the training intensity). It might also be used as an indicator of fatigue or overtraining in swimmers (i.e., decremented MSF might indicate fatigue, acute or chronic). In addition, it might be used to motivate or provide variety and novelty in a training program.

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Internal Stroke Motions and the Effective Coaching of Stroke Mechanics

David A. Levinson
Lockheed Palo Alto Research Laboratory
92-30/205
3251 Hanover Street
Palo Alto, California 94304

Abstract

It is shown that a swimmer's feedback control process is incompatible with stroke instruction expressed in terms of external motions (motions of swimmers' body parts relative to the pool), but that instructions expressed in terms of internal motions (motions of body parts relative to each other) are effective. Data taken from underwater film of an Olympic gold medalist freestyler are used to show that the path of the swimmer's hand relative to his torso is substantially different from the path of the hand in a pool-fixed reference frame, and an algorithm is provided for calculating coordinates of points in a torso-fixed reference frame in terms of the coordinates of the same points in the pool-fixed frame.

Introduction

The purpose of this article is twofold. The first is to bring to light a major conceptual flaw underlying the way many swimming coaches teach stroke mechanics; the second is to provide the information necessary to remedy this flaw.

At the heart of the matter to be discussed is the fact that swimming is a *feedback control* process. What does this mean? A feedback control process is one whose actual output is sensed and compared with a desired output; a signal depending on the difference between the two is "fed back" to an actuator which alters the actual output so as to bring it closer to the desired one. A familiar example of a system incorporating a feedback control process is the autopilot on an airplane. The autopilot senses the airplane's actual heading, compares it with the desired heading, and sends a signal to motors that move the airplane's control surfaces so as to drive to zero the difference between the actual heading and the desired heading.

Swimming is this sort of process. In swimming, four main sensory centers are used to provide feedback information: the eyes, which help the swimmer swim in a straight line and execute turns; the balance sensors in the inner ear, which help the swimmer to sense the directions of up and down; the pressure sensors on the hands and feet, which help the swimmer maintain a good "grip" on the water; and the sensors in the muscles that detect how the various body parts are configured *relative to each other*. Of these four, it is the last that plays a central role in the execution of proper stroke motions. When a swimmer performs a stroke, the *relative* arrangement of the swimmer's hand, forearm, upper arm, torso, etc. is sensed at each instant and is compared with the desired relative arrangement. The swimmer's muscles come into play in an attempt to drive to zero the difference between the actual relative arrangement of body parts and the desired relative arrangement. The only step in the feedback process not yet accounted for is how the swimmer knows at each point in the stroke what the "desired relative arrangement of body parts" is. This is what the swimmer must learn from the coach.

All of this becomes clear when one reflects on one of the most frustrating situations in the coaching of swimming, namely, the one that arises when the coach gives the swimmer an instruction intended to cause the swimmer to modify an improper stroke, whereupon the coach is greeted with a blank stare of incomprehension from the swimmer. All too frequently, this happens not as a result of the swimmer's inadequate intelligence, but because the coach has given the swimmer an instruction that cannot be executed. What is it about such an instruction that renders it unexecutable? It is simply that the coach is asking the swimmer to move a body part, such as a hand, *relative to the pool* in a desired manner. Since,

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as was stated previously, the swimmer employs a feedback control process requiring knowledge of the desired path of the hand *relative to other body parts*, such as the swimmer's torso, the swimmer cannot carry out the coach's instruction. In other words, the swimmer *must* have a correct stroke standard described to him in terms of *internal* motions, that is, motions of body parts relative to each other. How, then, do swimmers learn proper stroke mechanics from coaches who give instructions in conventional terms, that is, in terms of descriptions of *external* motions? The answer is that a lengthy trial and error process eventually leads to the swimmer's discovering the proper mechanics; and this process could be shortened considerably by giving the swimmer better instructions.

A specific, if simple, example helps to clarify these ideas. Figure 1a is a schematic representation of an overhead view of a swimmer standing on a pool deck with both of his arms held horizontally, parallel to the frontal plane of his torso, and perpendicular to the pool wall W to his right. The swimmer's elbows are locked, and the palms of his hands are facing forward. Since, as noted previously, visual feedback is not a factor in the execution of swimming strokes, suppose that the swimmer is wearing blacked out goggles, so that he cannot see anything. Imagine now that the coach asks the swimmer to rotate his right arm in a horizontal plane until the arm is parallel to W. This presents no difficulties for the swimmer, who easily performs the task, as shown in Figure 1b. Now the coach asks the swimmer to enter the water, and, floating vertically, position himself relative to W as in Figure 1a, temporarily peeking under his blacked out goggles for this purpose. The coach then asks the swimmer to replace his goggles and to repeat the maneuver he just performed while standing on the pool deck, that is, to rotate his right arm in a horizontal plane until the arm is parallel to W. The swimmer tries precisely what worked for him on the pool deck, that is, a 90 degree rotation of his arm relative to his torso, but, as a result of forces exerted by his arm and the water on each other, the swimmer ends up as shown in Figure 1c, much to the coach's displeasure. Because the swimmer's arm is not parallel to W, the coach has the swimmer reposition himself in accordance with Figure 1a as before, and then tells him to try once more to rotate his right arm in a horizontal plane until the arm is parallel to W. This time, the swimmer makes a guess and tries rotating his arm relative to his torso 110 degrees. Again this proves unsatisfactory. After many more unsuccessful attempts, the swimmer finally discovers that if he rotates his right arm relative to his torso 135 degrees, his coach says, "You've got it!" while gazing with great satisfaction at his swimmer who is now in the configuration shown in Figure 1d, his arm parallel to W. All of this painstaking coaching effort would have been unnecessary had the coach instructed the swimmer at the outset to perform the *internal* motion of rotating his right arm 135 degrees relative to his torso, instead of telling him to perform the *external* motion of rotating his arm 90 degrees relative to the pool wall. Of course, the coach would have had to know that the 135 degree internal motion does the job. More about this presently. The coaching problems brought to light in this simple example are compounded severely in connection with instruction on real swimming techniques, for here the arms undergo motions that are considerably more complex than simple rotations with locked elbows. Thus, it is even more crucial in real coaching situations than in this example for coaches to instruct swimmers on the subject of stroke mechanics in terms of internal rather than external motions.

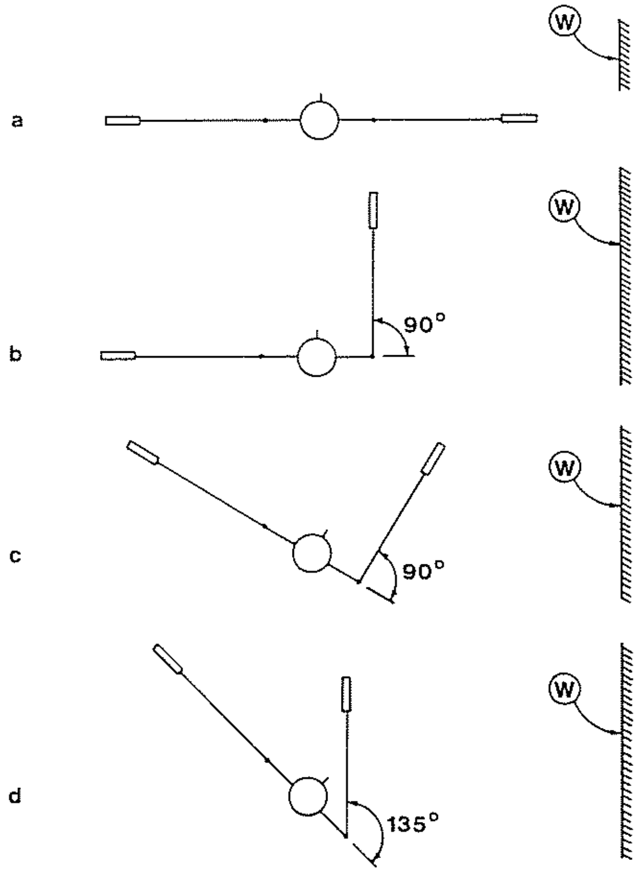

Figure 1. Example of ineffectiveness of external motions based coaching.

The internal motions principle is well known to astronauts [see, e.g., (3), (4)]. Although astronauts do have visual feedback, they have no water to push against when they float freely in space. Yet they can achieve any desired reorientation of their torsos relative to the stars by moving their arms and legs relative to their torsos in appropriate ways. What is relevant to swimming in this regard is that rookie astronauts, who have never before flown into space, but have been told during training how to perform the necessary internal motions, can perform these reorientation maneuvers expertly on their first try in orbit. Thus, there is a considerable body of evidence demonstrating the efficacy of using instructions expressed in terms of internal motion descriptions to teach humans to perform desired external motions.

In recent years, it has become increasingly popular for coaches to take underwater movies of champion swimmers [e.g., (1), (6)], and to use these to construct curves showing the underwater hand paths of swimmers. These curves then serve as the basis for detailed analyses of both the kinematics and kinetics of arm motions in swimming [e.g., (2), (5), (7)]; and many coaches employ these curves as instructional tools for swimmers, attempting to teach stroke mechanics by having the swimmers try to move their hands relative to the pool in accordance with the curves. But this is equivalent to what happens in the example considered previously (see Figure 1). Here a curve constructed from an underwater movie showing the motion of the right arm in connection with the Figure 1d maneuver would depict the arm rotating 90 degrees relative to W. Thus, a swimmer who saw a movie-derived curve of the hand path leading from the configuration of Figure 1a to that of Figure 1d would arrive at the incorrect configuration shown in Figure 1c when he attempted to reproduce the curve with his own hand. In contrast, a curve showing showing the 135 degree rotation of the arm relative to the torso, as depicted in Figure 1d, would lead the swimmer immediately to the Figure 1d configuration. What is needed, therefore, is a method for converting external motion information, such as that obtained from film, to internal motion information directly usable by the coach on the pool deck. This is the subject of the remainder of this article.

In what follows, the underwater path of a front crawl swimmer's fingertip relative to a set of pool-fixed axes is compared with the same path as projected onto two other sets of axes, one set translating relative to the pool with the swimmer's torso, but not rotating relative to the pool, and the other set fixed in the swimmer's torso. It is shown that these paths all differ substantially from each other, both quantitatively and qualitatively. Since the details of strokes differ from swimmer to swimmer, even among world class swimmers, the article concludes with an appendix containing an algorithm for finding the coordinates in torso-fixed axes of a point on a swimmer's hand during a front crawl arm pull when the coordinates in pool-fixed axes are known.

Example

To discuss in a precise way the path traced by a point on a swimmer's hand during the underwater portion of the front crawl armstroke, it is helpful to introduce three reference frames (see Figure 2) — the "pool frame" P, attached rigidly to the swimming pool; a "translating frame" T that moves across the pool with the swimmer's torso, but does not change its orientation with respect to P; and a "body frame" B, in which the swimmer's torso is fixed. Thus, T undergoes a purely translational motion in P, while B perform solely a simple rotational motion in T.

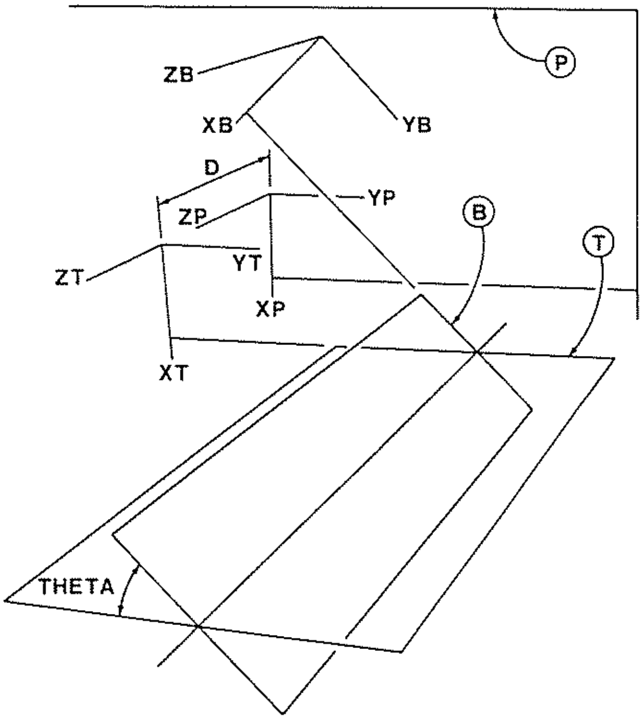

Figure 2. Reference frames and coordinate axes.

Three sets of orthogonal coordinate axes are of interest. Fixed in P are axes XP, YP, and ZP, with the positive XP axis pointing downward, the positive YP axis horizontal and pointing from right to left in the swimmer when the swimmer's frontal plane is horizontal, and the positive ZP axis pointing in the direction of motion of the swimmer. Axes XT, YT, and ZT are fixed in T and have the same orientations and positive directions as XP, YP, and ZP, respectively, at all times; ZT and ZP are colinear. Finally, axes XB, YB, and ZB are fixed in B, with XB pointing in the direction of the outward normal to the swimmer's frontal plane, YB pointing from right to left in the swimmer, and ZB parallel to ZP and ZT at all times, and pointing in the direction of the swimmer's motion.

D denotes the distance from the XP—YP plane to the XT—YT plane, and THETA is the angle between XT and XB (as well as the angle between YT and YB). Thus, D is the distance the swimmer has moved across the pool at a given instant, and THETA is the swimmer's roll angle at the same instant. When D = 0, one can see from Figure 2 that XT is coincidental with XP, YT with YP, and ZT with ZP; and, when THETA = 0, it is seen that XB is coincidental with XT, YB with YT, and ZB with ZT.

Figure 3 shows the projection, onto the YP—ZP plane, of the path of the right middle fingertip traced by a male Olympic freestyle gold medalist during one complete underwater pull.[1] On the curve, each point denoted by a little square corresponds to one photographic frame in a sequence taken at 66 frames per second. The entire pull lasts 57 frames. The view in Figure 3 is from directly above the swimmer, the vertical dashed line to the left of the curve is the centerline of the swimmer's body, and the direction of motion of the swimmer is from the bottom of the figure to the top. Note that point 57, corresponding to where the fingertip is at the end of the pull, is actually ahead of point 1, corresponding to where the fingertip is when the pull begins. It is well known that this manifestation of stroke efficiency is prevalent in world class swimmers.

When the same fingertip motion used to generate Figure 3 is projected onto the YT—ZT axes (see Appendix for details), Figure 4 results. Here, as is expected, the curve is longer than the one in Figure 3, since the fingertip now moves twice the length of the swimmer's arm in the negative ZT direction, whereas translation of the swimmer's torso resulted in an apparent shortening of the curve along the ZP axis in Figure 3. What may not be expected, however, is what one finds when one compares the portions of the two curves between points 1 and 32. In Figure 3, this portion of the curve corresponds clearly to a forward motion of the fingertip, but in Figure 4, the portion of the curve between points 1 and 18 is associated with almost no motion, and the portion between points 18 and 32 corresponds clearly to a *backward* motion of the fingertip. Hence, based on Figures 3 and 4, what should a coach tell a swimmer to do? Should the swimmer move his hand forward or backward in the water during the portion of the stroke associated with points 18 to 32? The resolution of this dilemma will be provided later in the Conclusions section of this article in quite general terms, but first it will be shown that failure to take a swimmer's rolling motion into account when attempting to analyze underwater movies of swimmers can lead to confusion just as severe as that arising when the translation of a swimmer's torso in the water is not taken into consideration.

Figure 5 shows the swimmer's roll angle time history corresponding to the fingertip motion discussed in connection with Figures 3 and 4. It can be seen from the figure that the stroke begins with the shoulder of the pulling arm rolled downward about 20 degrees. By frame 19

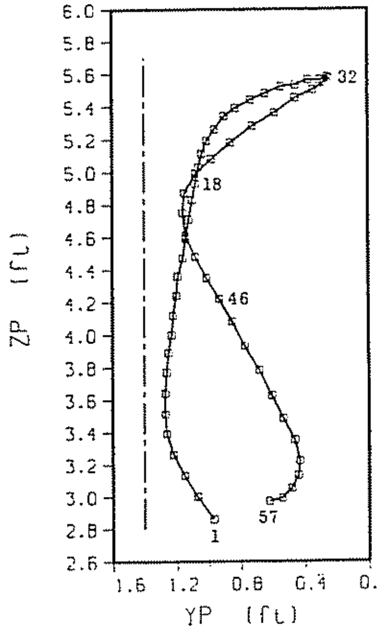

Figure 3. View from above of fingertip path in pool-fixed axes.

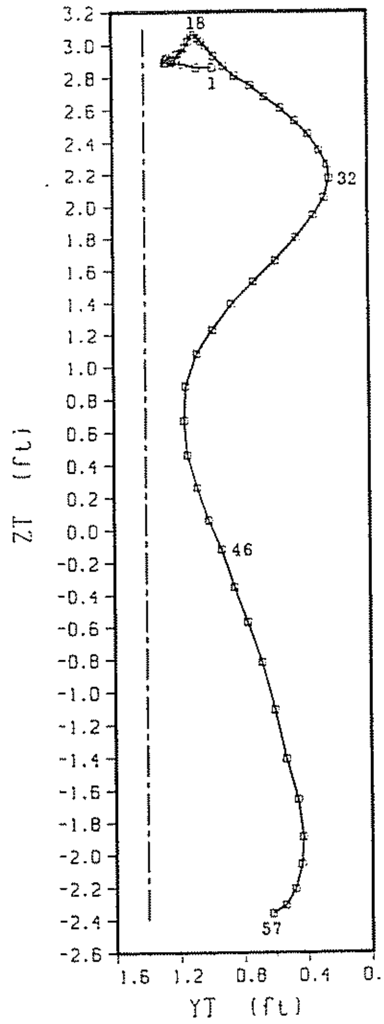

Figure 4. View from above of fingertip path in translating axes.

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[1] The author wishes to thank Dr. Robert E. Schleihauf for generously providing the data used directly to make Figures 3, 7, and 10, and employed by the author in performing the computations underlying Figures 4-6, 8-9, and 11.

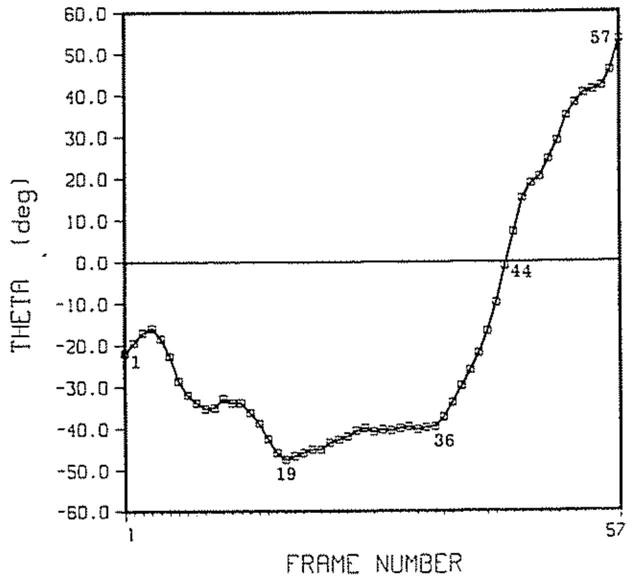

Figure 5. Roll angle time history of swimmer's torso.

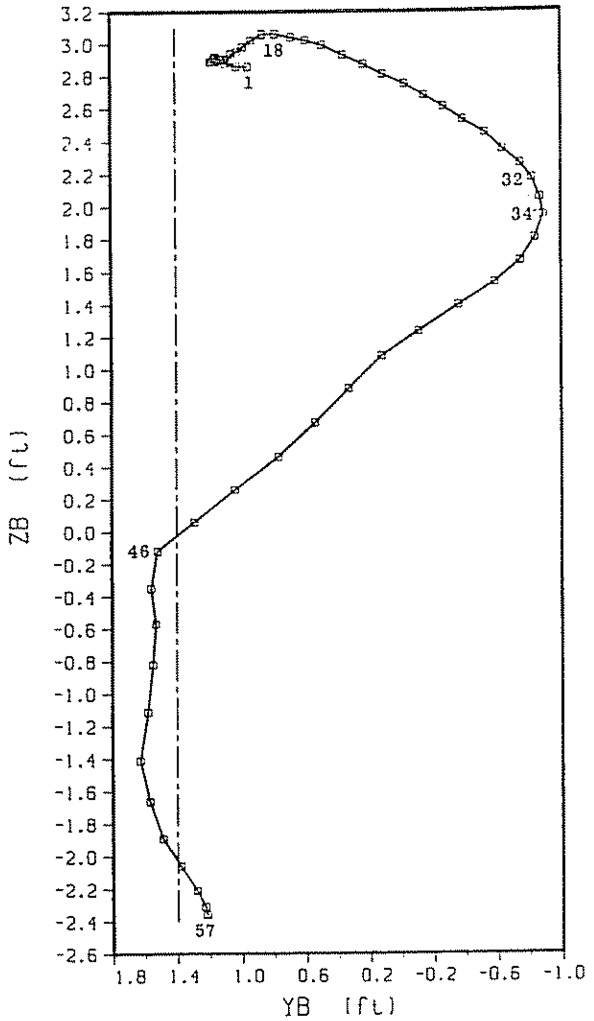

Figure 6. Frontal plane projection of fingertip path in body-fixed axes.

the shoulder has rotated to its maximum angle of minus 45 degrees, near which it dwells until frame 36, whereupon the swimmer rolls quite rapidly from about minus 40 degrees to more than plus 50 degrees during frames 36 through 57, this being the last third of the time interval occupied by the pull. The swimmer moves through positive roll angles only from frame 44 to frame 57, the last fourth of the pull interval. (This rapid body rotation at the end of the pull is probably due to a large moment about the swimmer's roll axis, applied at an instant of time corresponding to frame 36 by forces exerted on the swimmer's hand by the water.)

When the values of THETA plotted in Figure 5 are used in conjunction with the fingertip path coordinates plotted in Figure 4 (see Appendix for details), Figure 6 results. This is the projection of the path of the swimmer's fingertip onto the YB—ZB plane, the swimmer's frontal plane. Figure 6 differs significantly from Figures 3 and 4 in several respects. First, the initial portion of the curve in Figure 6 reveals a much wider excursion of the fingertip from the body centerline than one finds in Figures 3 and 4, as comparison of the locations of point 32 in the respective figures indicates. Moreover, the point of farthest separation of the fingertip from the centerline is point 32 in Figures 3 and 4, but point 34 in Figure 6. Perhaps most important, is the fact that the widely discussed "S-stroke," clearly visible in Figures 3 and 4, nearly disappears in Figure 6. Specifically, the portion of the pull from points 46 to 57, while curved in Figures 3 and 4, is nearly straight and parallel to the centerline in Figure 6. Finally, while the swimmer's fingertip does not cross the centerline in Figures 3 and 4, it does for about a third of the pulling path in Figure 6. Here again, the question arises as to what a coach should tell a swimmer. Should the swimmer's hand cross the centerline or shouldn't it? Should the swimmer attempt to imitate the non-crossing in Figures 3 and 4, or the crossing in Figure 6? As mentioned earlier in connection with comparisons of Figures 3 and 4, these kinds of questions will be discussed in general in the Conclusions section of this article. Before moving on, it is worth noting that the stroke pattern in Figure 6 more nearly resembles a butterfly stroke pattern than what is normally regarded as a crawl stroke pattern. Since butterfly swimmers don't roll, this means that the fingertip paths of freestylers and butterflyers relative to body-fixed axes are more nearly the same than has been previously surmised.

Turning now to the side views of the swimmer's fingertip path in each of the three sets of axes, one can begin with Figure 7, which shows the path projected onto the ZP—XP axes (see Figure 2). Here, the fingertip moves in what is nearly a closed loop, a loop which, however, opens widely when viewed in the ZT—XT axes (see Figure 2), as shown in Figure 8. As in the case of Figures 3 and 4, the portion of the path from points 18 to 32 reflects

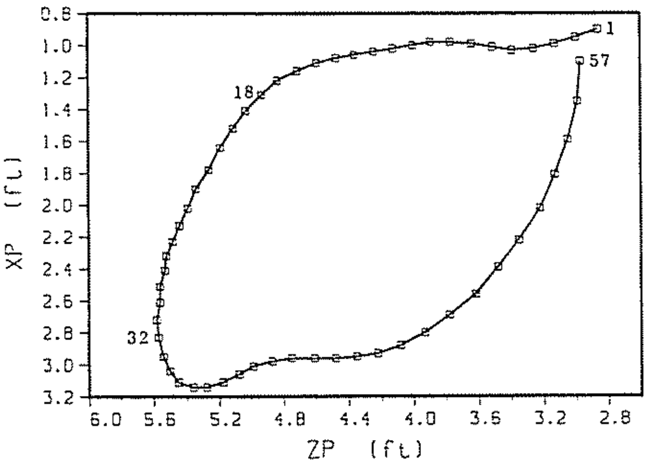

Figure 7. Side view of fingertip path in pool-fixed axes.

a forward motion in Figure 7, but a backward one in Figure 8. When rolling is taken into account, Figure 9 results, this being a sagittal plane projection of the fingertip path in body-fixed axes. As can be seen, the portion of the stroke corresponding to the first 42 frames is deeper in Figure 8 than in Figure 9, which reveals that much of the depth ascribed to the first part of a front crawl pull is a result of the downward roll of the shoulder on the pulling side, rather than as a result of the swimmer's hand being far away from the chest.

Figure 10 shows the front view of the hand path in both the YP—XP axes and the YT—XT axes (see Figure 2), where a distinct figure eight type of pattern is readily apparent, lying in its entirety to one side of the vertical plane (shown as a dashed line) passing through the swimmer's

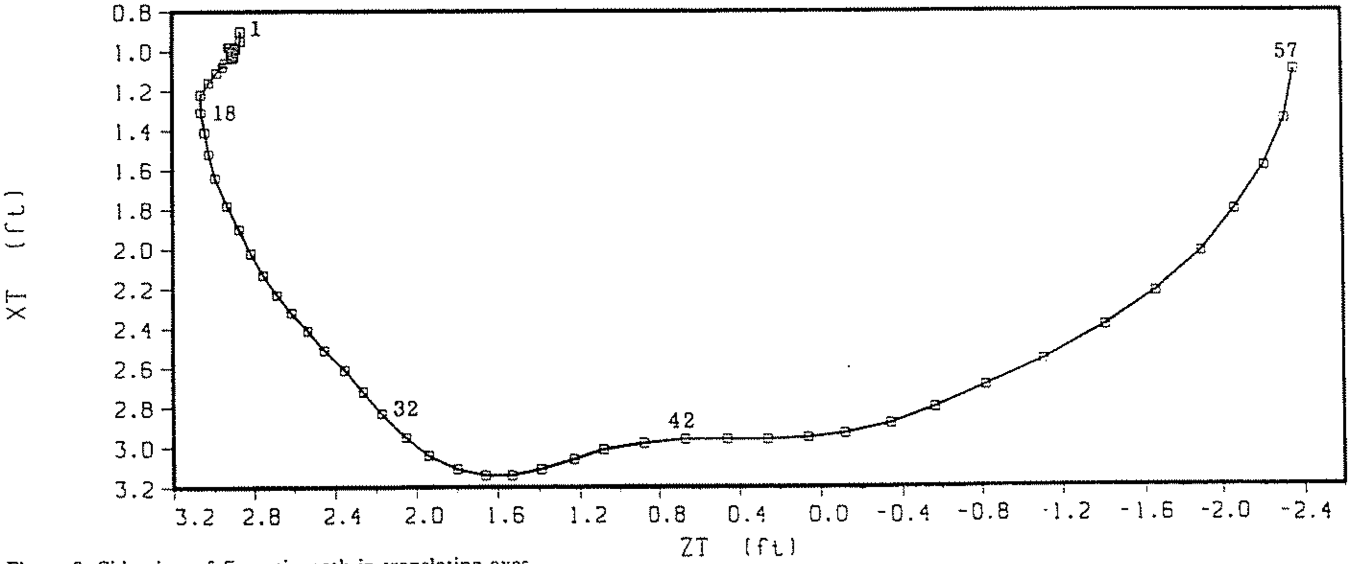

Figure 8. Side view of fingertip path in translating axes.

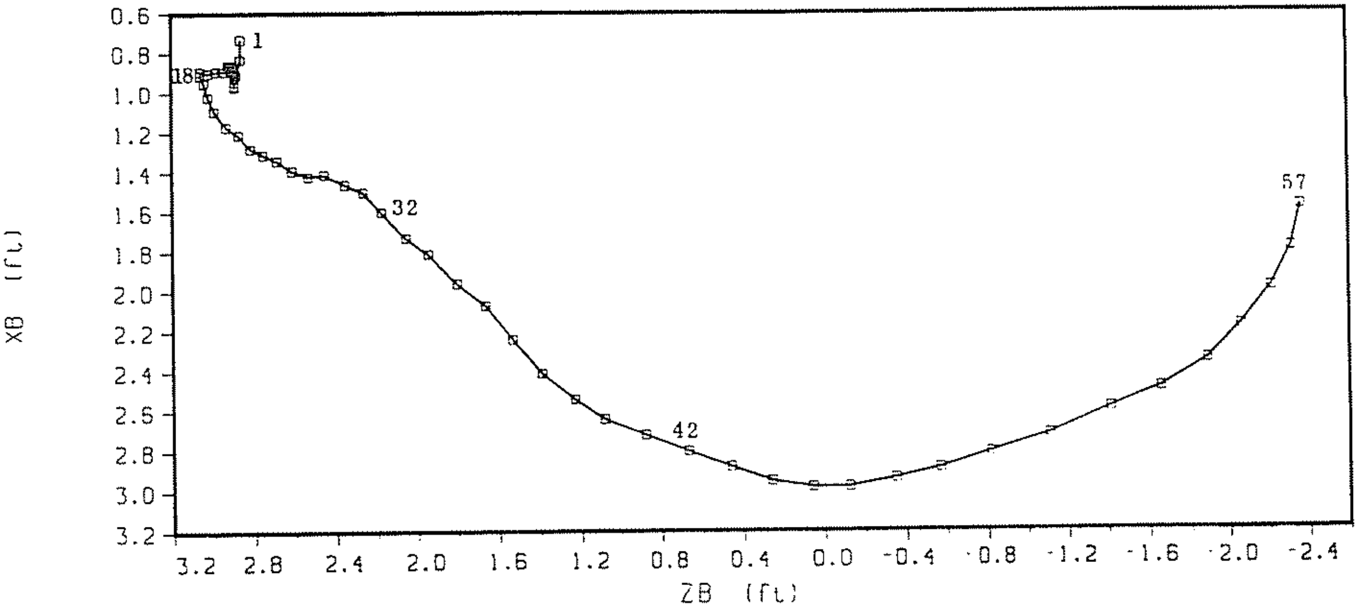

Figure 9. Sagittal plane projection of fingertip path in body-fixed axes.

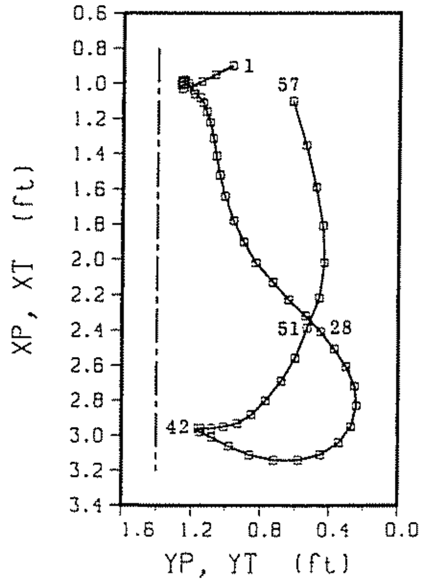

Figure 10. Front view of fingertip path in pool-fixed and translating axes.

centerline. The YB—XB plot (see Figure 2) of the front view, shown in Figure 11, tells a completely different story. Here, the figure eight pattern gives way (see points 28 through 51 in both figures) to a wider almost-closed loop that does, indeed, pass through the swimmer's sagittal plane (shown as a dashed line), that is, past the swimmer's centerline as viewed in body-fixed axes.

Conclusions

A case has been made in this article that the most effective way for coaches to teach stroke mechanics to swimmers is through the use of internal motion (motion of body parts relative to each other) descriptions, rather than external motion (motion of body parts relative to the pool) descriptions, because the former are compatible with swimmers' feedback control systems, whereas the latter are not.

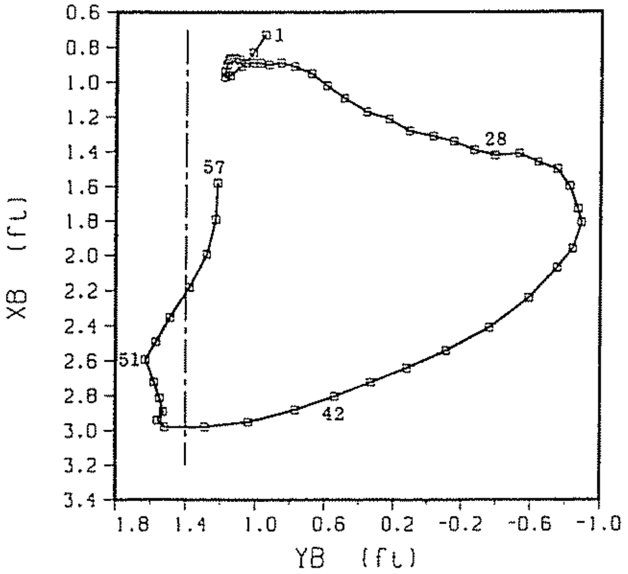

Figure 11. Front view of fingertip path in body-fixed axes.

In connection with actual data describing the hand motion of a world class freestyler, it was shown that internal hand motions in the front crawl differ substantially from external ones. In this connection, several questions arose as to which of several curves should be used as a guideline for instructing swimmers. It should be clear by now that Figures 6, 9, and 11, rather than Figures 3, 7, and 10, or Figures 4, 8, and 10 are the ones to use because only these are associated with internal motions. Thus, for example, the swimmer should be told that the portion of the pull from point 18 to point 32 represents a motion of the hand backward and to the right relative to the torso, as in Figures 6 and 9, not that it is a motion of the hand forward and to the right relative to the pool, as in Figures 3 and 7. Similarly, the swimmer should be told that the hand crosses the centerline of the torso, as in Figures 6 and 11, not that it doesn't cross the centerline, as in Figures 3 and 10.

Now, what does all of this mean to the swimming coach on the pool deck? The coach must be able to look at a swimmer in the water, identify what are external manifestations of internal stroke errors, and in real time supply the swimmer with a description of how to correct the stroke errors in terms of internal motions. At present, this may not be easy, because there does not yet exist a comprehensive manual for coaches that contains a set of externally observable stroke errors, together with the internal descriptions of the appropriate corrections. This is an important area for future research.

Appendix

Algorithm

Given, for N photographic frames, XPF(I), YPF(I), and ZPF(I) (I = 1,..., N), the XP, YP, and ZP coordinates (see Figure 2) of the swimmer's fingertip, determine XTF(I), YTF(I), and ZTF(I) (I = 1,..., N), the XT, YT, and ZT coordinates of the fingertip; and XBF(I), YBF(I), and ZBF(I) (I = 1,..., N), the XB, YB and ZB coordinates of the fingertip, by proceeding as follows:

1. Input XPF(I), YPF(I), ZPF(I) (I = 1,..., N)
2. Input ZPN(I) (I = 1,..., N), the ZP coordinates of a point on the swimmer's neck.
3. Form D(I), the value of D (see Figure 2) associated with frame I (I = 1,..., N) as
   D(I) = ZPN(I) − ZPN(1) (I = 1,..., N)
4. Form XTF(I), YTF(I), and ZTF(I) (I = 1,..., N) as
   XTF(I) = XPF(I) (I = 1,..., N)
   YTF(I) = YPF(I) (I = 1,..., N)
   ZTF(I) = ZPF(I) − D(I) (I = 1,..., N)

5. Input XA and YA, the XP and YP coordinates of any point on the swimmer's roll axis.
6. Input XPS(I) and YPS(I) (I = 1,..., N), the XP and YP coordinates of the center of the swimmer's shoulder joint on the pulling arm.
7. Form THETA(I), the value of THETA (see Figure 2) associated with frame I (I = 1,..., N) as
   THETA(I) = ARCTAN((XA − XPS(I))/(YA − YPS(I))) (I = 1,..., N)
8. Form STH(I) and CTH(I) (I = 1,..., N) as
   STH(I) = SIN(THETA (I)) (I = 1,..., N)
   CTH(I) = COS(THETA(I)) (I = 1,..., N)
9. Form XBF(I), YBF(I), and ZBF(I) (I = 1,..., N) as
   XBF(I) = XA * (1.0 − CTH(I)) + YA * STH(I) + XPF(I) * CTH(I) − YPF(I) * STH(I) (I = 1,..., N)
   YBF(I) = − XA * STH(I) + YA * (1.0 − CTH(I)) + XPF(I) * STH(I) + YPF(I) * CTH(I) (I = 1,..., N)
   ZBF(I) = ZTF(I) (I = 1,..., N)

Acknowledgment

The author wishes to thank Professor T. R. Kane of Stanford University for many stimulating discussions on the subject of human body motion.

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ERRATUM

Editor's note: Unfortunately, due to a typesetting error that occurred on Pg 23, paragraph 4, line 3 of the article entitled: "Energy Balance in Competitive Swimmers and Runners" by K.T. Jang, et al., the following sentence was *incorrect*: "To effectively manage a swimmer with a weight problem, it would appear prudent to implement a calorie restricted diet." The *correct* sentence should read: "To effectively manage a swimmer with a weight problem, it would appear prudent to have the swimmer first undergo dietary analysis prior to implementing a calorie restricted diet." We apologize to the authors for this error and any misunderstanding which may have resulted.

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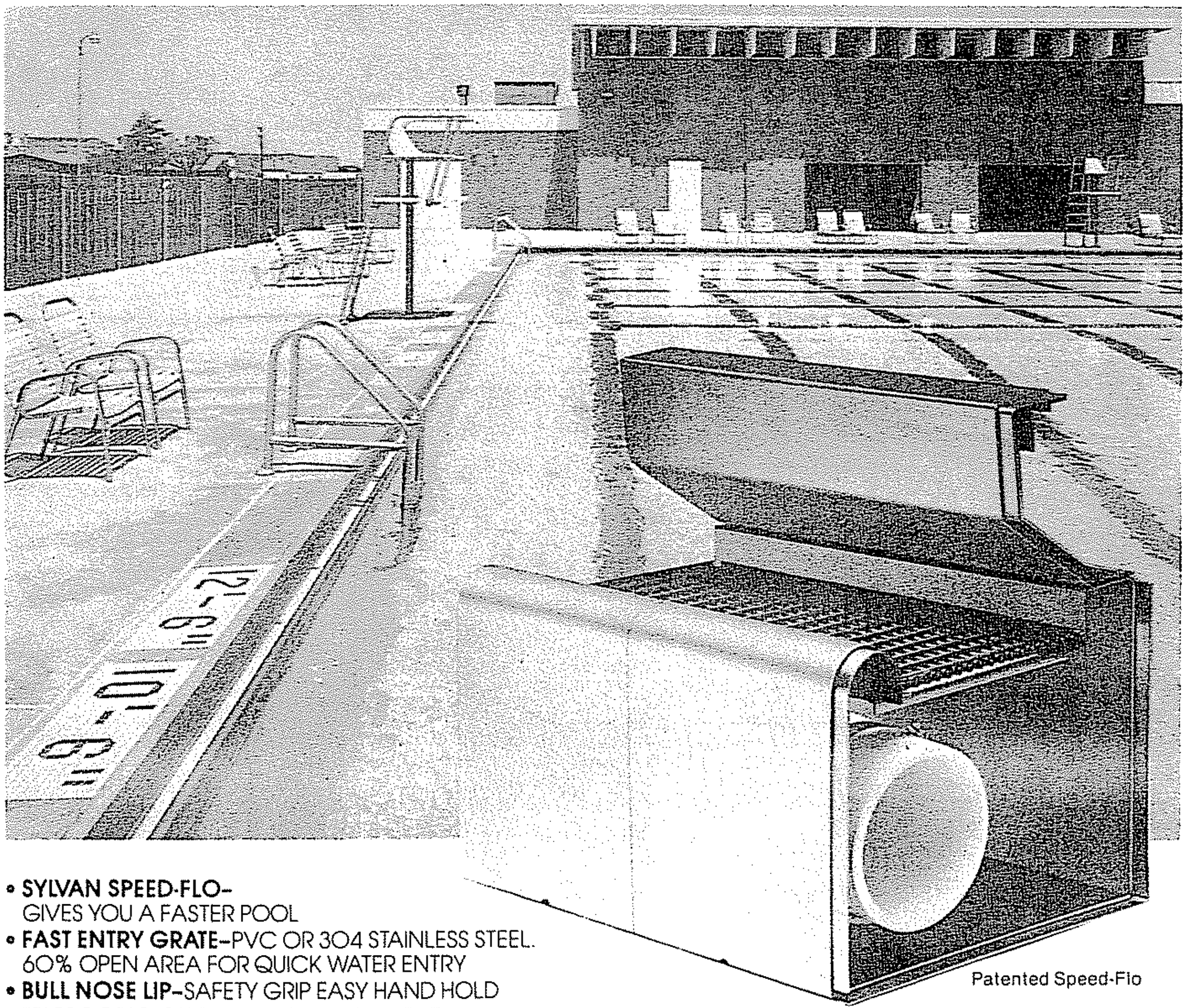

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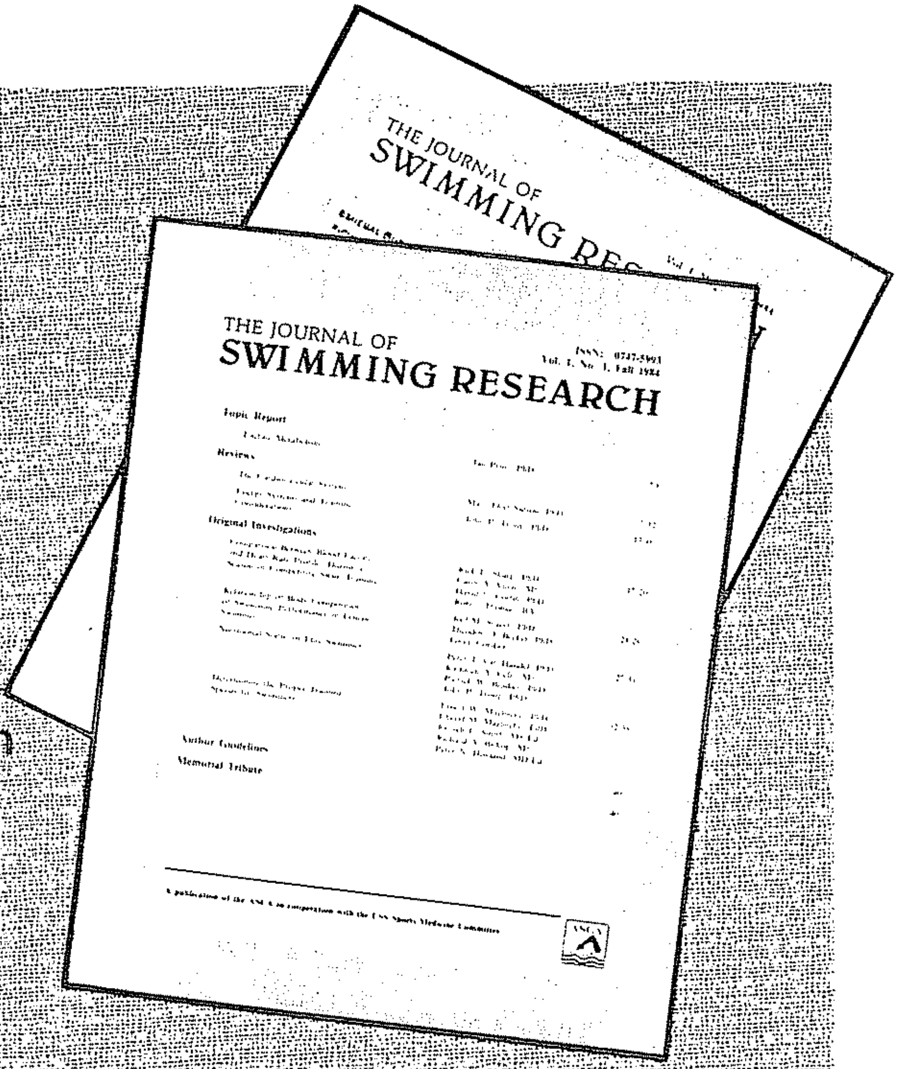

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