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Relationships of stroke rate, distance per stroke, and velocity in competitive swimming

ALBERT B. CRAIG, JR. and DAVID R. PENDERGAST

Department of Physiology, University of Rochester School of Medicine and Dentistry Rochester, New York 14642 and State University of New York at Buffalo Medical School Buffalo, New York 14214

ABSTRACT

CRAIG, ALBERT B., JR., and DAVID R. PENDERGAST. Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Med. Sci. Sports.* Vol. 11, No. 3, pp. 278-283, 1979. Competitive swimmers were asked to swim at a constant velocity (V) for short distances. They wore a collar to which was attached a fine non-elastic steel wire. The wire passed over two wheels of a device attached to one end of the pool. One wheel generated an impulse for every cm of forward movement and another wheel produced an electrical signal which was directly proportional to V. Measurements of distance and time were begun at definable points in the stroke cycle and were discontinued at the end of a predetermined number of strokes. In all of the four competitive strokes, front and back crawl, butterfly, and breaststroke, the V increased as a result of increasing the stroke rate ($\dot{S}$) and decreasing the distance per stroke (d/S). In the front crawl, the male and female swimmers who achieved the fastest V had the longest d/S at slow $\dot{S}$. The faster male swimmers also had greater percent decrease of the d/S at their maximal V than did the less skilled persons. The back crawl was similar to the front crawl except that maximal $\dot{S}$ and V were less. Increases of V of the butterfly were related almost entirely to increases in $\dot{S}$. Except at the highest V, d/S was decreased somewhat. In the breaststroke increased V was also associated with increasing $\dot{S}$, but the d/S decreased much more than in the other stroke styles. Fluctuations of velocity during the stroke cycle were least in the front and back crawl ($\pm$ 15-20%) and greatest in the butterfly and breaststroke (+45-50%). The results were compared to the $\dot{S}$ observed and the values for V and d/S calculated for a large group of swimmers competing in the 1976 U.S. Olympic Trials. The implications of the findings for coaching swimmers are discussed.

SWIMMING, BIOMECHANICS OF SWIMMING, FRONT CRAWL STROKE, BACK CRAWL STROKE, BUTTERFLY CRAWL STROKE, BREASTSTROKE, COACHING

Swimming, like most other methods of locomotion, involves the intermittent application of force which results in movement. In all of the stroke patterns used in swimming the mean velocity (V) is the product of the stroke rate ($\dot{S}$) and the distance moved through the water with each complete stroke (d/S).

$$V = \dot{S} \times d/S$$

In her review of the biomechanics of swimming, Miller (6) indicated that there had been no systematic study of these relationships in swimming. She also noted a need to describe the fluctuations in velocity which results from the intermittent application of force. The current investigation was designed to study these basic relationships between $\dot{S}$, d/S, and V in competitive swimmers.

METHODS

The subjects for these experiments were competitive swimmers of varying degrees of skill. All of them were active in swimming competition at the time they were studied. Two of the front crawl swimmers held national collegiate swimming records. One backstroker and one breaststroker had reached the finals in the national intercollegiate championships. None of the other swimmers had these degrees of skill but all were members of their college swimming teams.

The subjects were instructed to push off from the end of the pool and to swim one length (22 m) at a constant velocity using minimum $\dot{S}$ and trying to achieve maximum d/S. Repeated swims were made from very slow to what the subject felt was his or her fastest speed. In order to define a maximal V, it was necessary to urge the swimmers to increase the $\dot{S}$ even more than that associated with what they thought was their fastest velocity. When an increase in the stroke rate resulted in either no further increase or an actual decrease in V, it was possible to identify the maximal V. The time and distance to swim a pre-determined number of strokes were measured during each swim and from these data the $\dot{S}$, d/S and mean V were calculated.

The swimmers wore a light aluminum collar to which was attached a fine (0.25 mm diameter) malleable stainless steel wire which had no appreciable elasticity. This wire was pulled from the "swim-meter" which was fixed to the end of the pool. A fishing reel on this device was adjusted to produce a .25-.30 kp drag on the line. The wire passed over a wheel which was slotted at intervals corresponding to 1 cm forward movement of the line. The electronic circuit counted the number of times a light signal falling on a photosensitive diode was interrupted to measure the distance of the swim. The wire also passed over another wheel which was attached to a direct current generator. The output signal which represented the instantaneous velocity of the swimmer was recorded at a paper speed of 25 mm/sec. The voltage was directly proportional to the V over the range of calibration (0-3.5 m/sec).

During each swim an observer repeatedly pressed a

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hand held switch at a well defined point of the swimmer's stroke cycle. These signals were recorded on the second channel of the polygraph. The electronic circuitry was such that the measurement of distance and time began with the first signal. After a pre-determined number of strokes the measurements of time and distance were automatically stopped. A digital readout of distance, time, and number of strokes counted was used for the calculation of $\dot{S}$, d/S and V.

Calibration of the measurement of distance was done by pulling the wire through a measured 10 m pathway. This was done over the range of velocities observed during swimming. Calibration was also done by having a subject walk this 10 m distance with the wire attached to the subject's knee in order to produce fluctuations. Either method indicated that the error of the distance measurement was no greater than 0.5%. The clock was accurate to less than 0.5 sec per hour.

Each individual's curve showing the relationship of $\dot{S}$ and V was plotted, and the best fit was drawn by hand. Maximal d/S which occurred at the slow stroke rates was measured by the slope of a line fitted by eye between origin and the tangent to the curve relating $\dot{S}$ and V. The slope of this line is $\dot{S}$/V, i.e. d/S. At the maximal V the individual's $\dot{S}$ and d/S were also defined. The d/S at maximal V was compared to the maximal d/S and was expressed as a percent decrease of d/S, Δd/S.

$$\Delta d/S = 100 - \left(\frac{d/S \text{ at max } V}{\max d/S} \times 100\right)$$

The stroke rate-velocity curves ($\dot{S}$-V) for males and females swimming the different stroke patterns were developed from the data derived from each individual's graph. The individuals' V at selected stroke rates were tabulated and averaged.

The fluctuations of the V during the stroke were assessed by measuring the maximal and minimal peaks from the recording of instantaneous velocity. These peaks were expressed as a percent of the mean velocity during the swim. The fluctuations of each subject for selected ranges of velocity in each stroke pattern were averaged. As the wire was attached to the swimmer's neck, there was the possibility that assessment of fluctuations in velocity may not represent exactly movements of center of the mass. This problem was most obvious in the breaststroke and the butterfly in which there are significant vertical displacements during the stroke cycle. In the front and back crawl strokes there is virtually no vertical movement of the trunk. During swimming the body rotates around the center of air (lungs), and the use of the neck as the point of attachment is probably preferable to using the waist (7).

In order to relate these data to actual competitive swimming, we arranged to attend the U.S. Olympic Swimming Trials in 1976 at which time the selection of members of the U.S. Team was made. This competition was held in a 50 m pool, and the times of every race were recorded electronically. Stroke rates during each lap were measured by three observers who were seated on a balcony located at one end of the natatorium. Using an electronic stopwatch which could be read to 0.01 sec, each observer measured the time for five strokes during each lap for two swimmers. The average $\dot{S}$ for each swimmer was then calculated. Many races included 8 swimmers, and the competitors in each outer lane were not observed. The data from the preliminary races were used as more subjects were involved than in the final events.

The calculation of the mean V from the official time and distance of the race results in an over-estimation of the mean swimming V. The V of a swimmer leaving the starting block or pushing off from the side of the pool after each turn is greater than the mean swimming V. East estimated the effect of the start and turns from motion pictures made during a New Zealand National Swimming Championship (3). Using his data, it was estimated that calculation of mean velocity from the total distance and time of the race probably overestimated the true swimming velocity by 3.0% and 2.6% in the 100 m and 1500 m swims respectively. As these errors are systematic and relatively small, they probably do not significantly influence the general conclusions.

The differences between mean values were tested using the Student t test and were considered significant if p were less than 0.05.

RESULTS

The relationships of $\dot{S}$ and V in the four stroke patterns used in swimming competition are shown in Figure 1. The common feature of these curves is that increasing V was achieved by a combination of an increase in $\dot{S}$ and a decrease of d/S. In the front crawl, back crawl, and butterfly strokes it was possible to define the $\dot{S}$ and V at the maximal d/S (Table 1). At maximal d/S, the d/S s and $\dot{S}$ s in the front as compared to the back crawl were not different for either the males or the females. However, the values for V at maximal d/S were slower in the back than in the front crawl. Maximal values for V of the front crawl were greater than those in the back crawl. This difference was accounted for by the observation that values for $\dot{S}$ at maximal V were less in the supine as compared to the prone position.

The relationships of $\dot{S}$, d/S, and V in the butterfly stroke were different from the crawl strokes. The increase of V from the slowest speeds up to 80% of the maximal V for females and 94% for the males was accounted for entirely by the increased $\dot{S}$. In these ranges of V, d/S was constant. Even at maximal V, the Δd/S was only 18 and 15% for males and females, respectively. In the crawl strokes the mean Δd/S s were 30% and 24% for males and females respectively.

These patterns in the butterfly can be contrasted to those in the conventional breaststroke where the increased values for V related to greater $\dot{S}$ were associated with marked reduction of d/S. At 60 S/min the d/S was 45% of the d/S used at 20 S/min, and this relative shortening of

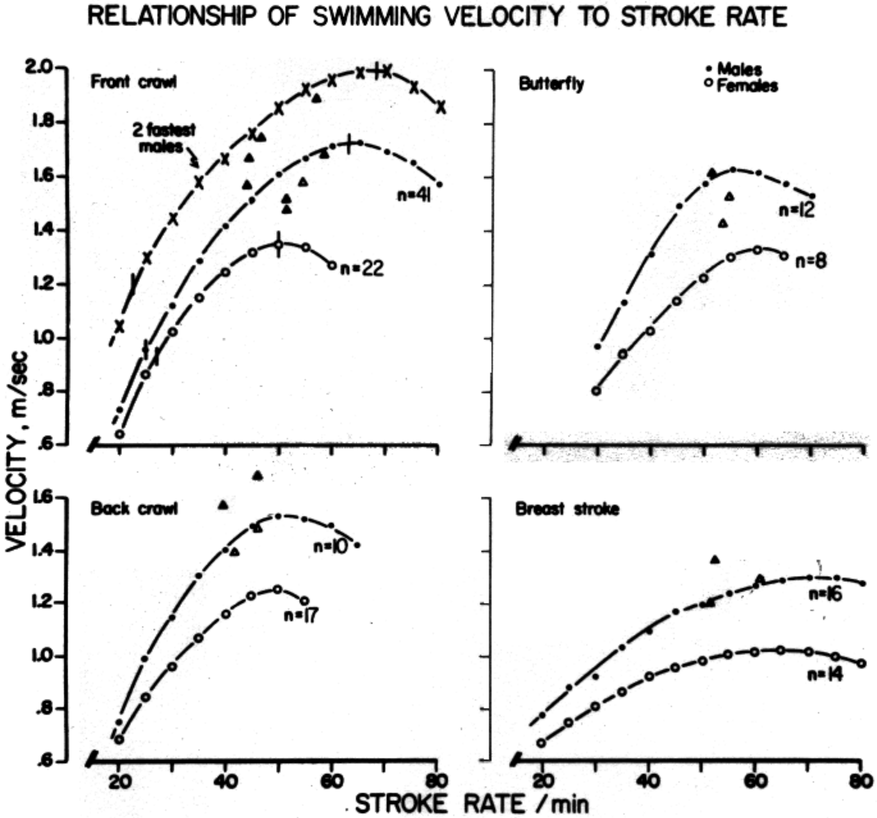

Figure 1—The curves indicate the relationships of $\dot{S}$ and V. On these graphs the d/S can be represented by a straight line from the origin to any point on the curve. The slope of such a line is a measure of d/S. The solid and open triangles indicate the results from the Olympic Trials for the male and female swimmers respectively. On each graph the triangles indicating the fastest V s were from 100 m races. In the front crawl the triangles showing the next two slower velocities for the males and females were from the 200 and 400 m races. The slowest velocities were observed in the 800 m event for females and the 1500 m for the males. In the other strokes the slower velocities were obtained in the 200 m races. The vertical lines on the S-V curves for the front crawl indicate the $\dot{S}$ at maximal d/S on the left side and the $\dot{S}$ at maximal V on the peaks of the curves.

TABLE 1: $\dot{S}$, V, and d/S relationships of competitive swimmers.

		At maximal d/S			At maximal V			
	n	$\dot{S}$ S/min	V m/sec	d/S m/S	$\dot{S}$ S/min	V m/sec	d/S m/S	Δd/S %
Front Crawl								
Males	41	26 ± 1.2*	1.02 ± .03	2.35 ± .07	63 ± 1.1	1.69 ± .02	1.62 ± .03	32 ± 1.8
Females	22	26 ± 1.2	.88 ± .03	2.04 ± .07	55 ± .07	1.43 ± .03	1.57 ± .04	24 ± 2.5
Back Crawl								
Males	10	22 ± .8	.90 ± .03	2.47 ± .08	50 ± 2.5	1.46 ± .04	1.79 ± .07	27 ± 2.1
Females	17	23 ± 1.2	.78 ± .03	2.03 ± .15	47 ± 1.4	1.21 ± .07	1.54 ± .07	24 ± 3.4
Butterfly								
Males	12	29 ± 2.1	1.00 ± .06	2.09 ± .07	56 ± 1.4	1.59 ± .04	1.71 ± .06	18 ± 2.1
Females	8	32 ± 2.8	.87 ± .06	1.66 ± .05	56 ± 2.5	1.30 ± .04	1.40 ± .04	15 ± 3.1

*S.E.

the stroke was the same for the males and the females. It was not possible to define either the point of the maximal d/S or maximal V in many of the individual curves for breaststrokers, and, therefore, average values are not given in Table 1. Many of these swimmers were able to maintain V at stroke rates greater than 70 S/min.

The largest group of swimmers studied were those swimming the front crawl and the two national record holders had the greatest maximal velocities of 2.0 m/sec. It was possible to identify certain characteristics of the $\dot{S}$-V curves of the people having different maximal V. The fastest swimmers had the longest d/S at submaximal V. There was a positive correlation between maximal d/S and maximal V (r = .52 for males and .59 for females). It was also noticed that the fastest male swimmers had a greater Δd/S at maximal V (r = .52), but this correlation was not statistically significant for the females. The smaller ranges of maximal V and fewer subjects in the other stroke patterns may have precluded obtaining similar statistically significant relationships.

The average fluctuations of speed were calculated for the four different stroke patterns. Minimum and maximal speeds were compared to the mean V in the ranges of 0.8-1.0, 1.0-1.2, 1.2-1.4, and when there were enough data, 1.4-1.6 m/sec. Fluctuations increased as the V increased, but when they were expressed as a per cent of the V, they were independent of the V. The average fluctuations are shown in Figure 2. The fluctuations in the breaststroke and butterfly were about twice those in the crawl strokes. In both the back crawl and breaststroke the minimal speed was significantly farther from the mean V than was the maximal speed. The front crawl and butterfly strokes were quite symmetrical.

The observations made at the Olympic Trials are sum-

TABLE 2: $\dot{S}$, V, and d/S during the U.S. Olympic Trials, 1976.

	Males				Females			
Event	n	$\dot{S}$ S/min	V m/sec	d/S m/S	n	$\dot{S}$ S/min	V m/sec	d/S m/S
100 m Freestyle	24	57 ± 1.0*	$1.92 \pm .01$	$2.03 \pm .03$	27	58 ± 1.1	$1.69 \pm .01$	$1.76 \pm .03$
200 m Freestyle	19	$46 \pm .9$	$1.75 \pm .01$	$2.27 \pm .04$	20	55 ± 1.1	$1.58 \pm .01$	$1.75 \pm .04$
400 m Freestyle	18	44 ± 1.1	$1.67 \pm .01$	$2.28 \pm .06$	22	52 ± 1.0	$1.52 \pm .01$	$1.78 \pm .03$
800 m Freestyle					22	$51 \pm .6$	$1.48 \pm .01$	$1.73 \pm .02$
1500 m Freestyle	28	$44 \pm .6$	$1.57 \pm .01$	$2.15 \pm .03$				
100 m Back Crawl	18	$46 \pm .7$	$1.70 \pm .01$	$2.24 \pm .03$	21	$46 \pm .7$	$1.49 \pm .01$	$1.94 \pm .03$
200 m Back Crawl	24	$39 \pm .6$	$1.57 \pm .01$	$2.40 \pm .03$	22	$42 \pm .6$	$1.40 \pm .01$	$2.02 \pm .03$
100 m Butterfly	28	$54 \pm .5$	$1.78 \pm .01$	$1.99 \pm .02$	36	$55 \pm .6$	$1.53 \pm .01$	$1.70 \pm .02$
200 m Butterfly	20	$51 \pm .5$	$1.62 \pm .01$	$1.91 \pm .02$	32	$53 \pm .6$	$1.43 \pm .01$	$1.61 \pm .02$
100 m Breaststroke	28	$61 \pm .8$	$1.48 \pm .01$	$1.46 \pm .02$	22	61 ± 1.3	$1.29 \pm .01$	$1.28 \pm .02$
200 m Breaststroke	16	52 ± 1.2	$1.36 \pm .01$	$1.58 \pm .04$	16	$51 \pm .9$	$1.21 \pm .01$	$1.42 \pm .03$

*S.E.

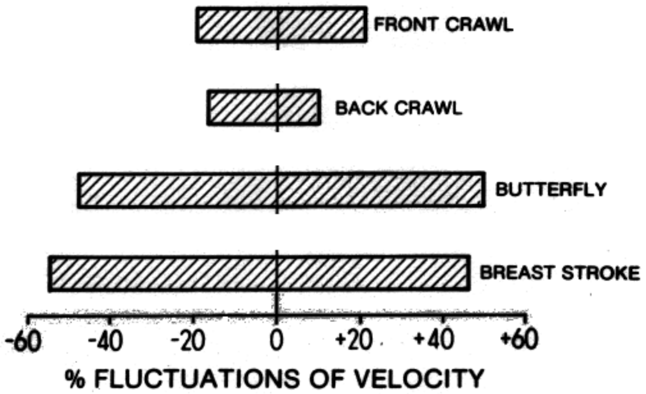

Figure 2—The mean fluctuations expressed as a per cent of the V are shown for the four different stroke patterns.

marized in Table 2 and are also shown in Figure 1. The results of the 100 and 200 m races for the males swimming the front crawl, back crawl and breaststroke indicated that the greater V of the shorter races were achieved by a combination of increasing the $\dot{S}$ and decreasing d/S. These observations were also true for the females swimming the back crawl and breaststroke. As shown in Figure 1 these results from the 100 and 200 m events probably represent a short segment of the $\dot{S}$-V curves for very skilled swimmers.

In contrast, all of the freestyle events for females and the 400 and 1500 m events for males were swum with faster S than would be predicted from the $\dot{S}$-V curves. The different values for V in the 100, 200, and 400 freestyle races for females were accounted for almost solely by differences in $\dot{S}$. There were no significant differences in the d/S. The 1500 m race for males was swum with the same $\dot{S}$ as was used for the 400 m event but the d/S was less. The slower V of the 800 m as compared to the 400 m event for females is also accounted for more by a decrease of the d/S than a change of $\dot{S}$.

The results from the butterfly races for both males and females indicated a different $\dot{S}$-V relationship. The increases of the $\dot{S}$ in the 100 m as compared to the 200 m event were much less than in the other stroke patterns. The 100 m butterfly race was swum with a longer d/S than used for 200 m. This latter result contrasts to the general observation that increased V of the shorter events was associated with a decrease of the d/S.

In the freestyle races longer than 100 m, the $\dot{S}$ which the females used were considerably faster than those observed for the males. In the other three swimming styles, the values for $\dot{S}$ were the same for both sexes.

DISCUSSION

Increased V is achieved by a combination of increasing $\dot{S}$ and decreasing d/S in all of the four competitive strokes. The $\dot{S}$-V curve for an individual swimmer indicates the minimal $\dot{S}$ for any V. A given V can be swum with a faster but not slower $\dot{S}$. As the V increases, the range of possible $\dot{S}$ decreases, and maximal V occurs at a unique combination of $\dot{S}$ and d/S. These relationships apply to the front and back crawl and the butterfly strokes. In the breaststroke some subjects were able to maintain their maximal V using a range of $\dot{S}$ even to 80-90 S/min.

This ability to adjust $\dot{S}$ and d/S seems to be learned as part of training for competition, and once these skills are learned they seem to be maintained. Attempts to define $\dot{S}$-V relationships for 3 recreational swimmers were unsuccessful. They were not able to swim at constant speeds nor were the points on the curve reproducible. The $\dot{S}$-V curves of 3 individuals who had not been swimming competitively for a number of years had the same form as those shown in Figure 1. As the repetitive swims required to develop such a curve are all of a short duration, the general conditioning for swimming does not seem to be a factor. The $\dot{S}$-V curve indicates a person's skill in each stroke pattern.

In the front crawl the ability to achieve fast V was directly related to maximal d/S. The individuals who had the longest d/S at slow $\dot{S}$ had the greatest maximal V. This result implies that helping swimmers improve performance should probably involve considerable practice swimming with slow $\dot{S}$: (20-30/min) with the goal of achieving a longer d/S. If a swimmer does not have a long d/S, there is less latitude for "shortening" and a greater dependence on $\dot{S}$ to swim fast.

Although it is tempting to compare the male and female swimmers for whom $\dot{S}$-V curves were developed, there is no way of knowing if the groups were relatively the same in their competitive abilities. However, it is probably safe to assume that the swimmers competing in the Olympic Trials represented the most skilled swimmers of both sexes, and comparisons can be made.

In the 100 and 200 m front crawl, back crawl, and breaststroke events for males and in these last two types of swimming for females, the $\dot{S}$-V relationships appeared to represent a small part of the complete curve. We were fortunate to study two very skilled front crawl swimmers and to compare their $\dot{S}$-V curves to the $\dot{S}$-V relationships observed at the Olympic Trials. The 100 and 200 m freestyle events in which the swimmers used the front crawl cannot be swum at maximal V. However, the $\dot{S}$ used in these events seemed to be minimal for the V achieved. These results imply that if one knows the $\dot{S}$-V relationships of an individual, it might be profitable to practice swimming fast with minimal $\dot{S}$. This attention to $\dot{S}$ during competition seemed to be helpful to the men's and women's teams at this University. In coaching parlance, this has been called "swimming on your curve".

In freestyle races longer than 200 m, the $\dot{S}$ which the males used were faster than would be predicted if the swimmers swam "on the curve". The same velocity could have been achieved at a slower $\dot{S}$. However, slower $\dot{S}$ would demand a greater force for each stroke. It is possible that swimming with a slower $\dot{S}$ would result in undue local muscular fatigue for these distances and times. The observation of the dependence of V almost completely on $\dot{S}$ for the females suggests that they may, in fact, be limited by local muscle power and/or endurance. The 200 m butterfly events for both sexes were swum with a shorter d/S than used for the 100 m races. Again, this choice of a shorter rather than longer d/S as in other styles may be related to local muscle fatigue which is particularly severe in this stroke pattern. These results suggest that training for swimming should probably involve specific exercises to increase muscle strength, power, and endurance. Such practice may improve a swimmer's ability to use a combination of $\dot{S}$ and d/S which is near their $\dot{S}$-V curve.

At present, it is difficult to relate the current studies to the energetics of swimming. As has been indicated (2,4,5,7) mechanical power output during swimming at a constant speed is the product of the force required to overcome the drag and the V. This power output is also the product of the rate of energy produced and the swimmer's efficiency. Evaluation of swimming ability involves consideration of both drag and efficiency (7).

A skilled swimmer can swim the front crawl at 1 m/sec with a variety of $\dot{S}$ from about 20 to 50 S/min. At the slower $\dot{S}$ the pattern of movement of the arm through the water must be basically like those which are recommended as optimal (1) and which probably result in the greatest d/S. At faster $\dot{S}$ the arm can be more flexed at the elbow and the hand slanted such that less force is exerted against the water. It would seem that such changes in technique would imply a decrease in efficiency. However, it is possible that using faster $\dot{S}$ to go 1.0 m/sec might decrease the body drag as well as the efficiency. If faster $\dot{S}$ decrease both drag and efficiency proportionally, the oxygen costs of swimming a given distance would remain the same (7). As noted above, swimmers using the front crawl stroke in competition do not select the minimal $\dot{S}$ in the longer races. As the effects of varying $\dot{S}$ and d/S at a given V on the force required to overcome drag and on the efficiency are unknown, it is not possible to explain these observations.

Present assessments of the energy requirements for swimming assume that the speed fluctuations with each stroke are negligible (2). In the butterfly and breaststrokes fluctuations of speed are marked and as indicated in Figure 2 the maximal and minimum variations are from 45 to 55% from the mean V. The oxygen costs of such accelerations must be considerable (4). In the back crawl and breaststroke the minimal speed during the stroke cycle was farther from the mean V than was the peak speed. In the breaststroke the minimal speed was associated with the flexion of the knee and to a lesser extent the hip in preparation for the kick. These motions result in a sudden increase of the body drag. In the backstroke leg action may also be a factor in the decrease of the speed. Many backstrokers tend to flex the knee as the opposite arm enters the water. This so-called "foot drop" was often quite pronounced and was apparent as a sudden deceleration on the record of the instantaneous velocity.

At present, it is possible to relate this study of the relationships of $\dot{S}$, d/S, and V to competitive swimming in only a general manner. All races must be swum at less than maximal V, and V will be limited by the total amount of energy available for the time of the race. The swimmer must select an optimal combination of $\dot{S}$ and d/S. This choice also involves considerations of local muscle power and endurance. In all of the stroke patterns used in competition, there are fluctuations of speed which are also related to $\dot{S}$, d/S, and energetics. It is not yet possible to analyze the combination of $\dot{S}$ and d/S which would result in the fastest times for all of the different races in swimming.

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