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ORIGINAL INVESTIGATIONS

Velocity, stroke rate, and distance per stroke during elite swimming competition

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ABSTRACT

CRAIG, A.B., JR., P.L. SKEHAN, J.A. PAWELCZYK, and W.L. BOOMER. Velocity, stroke rate, and distance per stroke during elite swimming competition. *Med. Sci. Sports Exerc.*, Vol. 17, No. 6, pp. 625-634, 1985. The mean velocity of 9 out of 10 women's events during the U.S. Olympic Swimming Trials was greater in 1984 as compared to 1976. Three of the 10 men's events showed improvement. In 9 out of these 12 events, the increased velocity was accounted for by increased distance per stroke (range, 4 to 16%), and in 8 there was also a decrease in stroke rate (range, −3 to −13%). In the women's 100-m butterfly and 100-m backstroke, increased velocity was due solely to faster stroke rates. The finalists in each event were compared to those whose velocities were 3-7% slower. In almost all events and stroke styles, the finalists achieved greater distances per stroke than did the slower group. In the men's events increased distance per stroke was associated with decreased stroke rate, except in the backstroke, in which both were increased for the finalists. Although the faster women swimmers generally had greater distances per stroke, they were more dependent than men on faster stroke rates to achieve superiority. The profile of velocity for races of 200 m and longer indicated that as fatigue developed the distance per stroke decreased. The faster swimmers compensated for this change by maintaining or increasing stroke rate more than did their slower competitors. This study indicates that improvements and superiority in stroke mechanics are reflected in the stroke rate and distance per stroke used to swim a race.

SWIMMING, VELOCITY, STROKE RATE, DISTANCE PER STROKE, U.S. OLYMPIC TRIALS

Swimming speed or velocity is the product of the stroke rate and the distance traveled with each stroke cycle. These relationships and their changes with training have been examined in competitive swimmers (2-5). They have also been described for a group of elite swimmers observed during the United States Olympic Swimming Trials in 1976 (2). These latter studies were repeated during the U.S. Olympic Trials in June 1984. The changes in velocity of this elite group of swimmers have a defined relationship to the changes in world records (1).

Since 1976 world records in swimming, expressed in terms of velocity, have increased 3.0% for women's events and 2.3% for men's. In the current study the performance in the 1984 trials were analyzed, and the results were compared with those from the 1976 trials. The velocity, stroke rate, and distance per stroke relationships of the eight swimmers who swam in the finals in each event were also compared to those of the competitors whose velocities were 3 to 7% slower than those of the finalists. Changes in stroke rate and distance per stroke during selected races also helped identify the characteristics of the finalists which accounted for their faster velocities.

METHODS

The methods employed in the current study were the same as those used in 1976 (2). Four observers sat on a balcony at one end of the natatorium and had an unobstructed view of the 8-lane pool. Each person measured the time for five complete stroke cycles each lap for 2 of the 8 swimmers. These times were used to calculate stroke rates. Velocities were calculated from the printed output of the automatic timing device. In the previous study (2) this information was available for each 100-m increment of the races, but in the current investigation there were touch pads at each end of the pool, and the times for each 50 m were known. Distances per stroke were calculated by dividing the velocities by the stroke rates.

These calculations overestimated the distance traveled with each stroke cycle. Part of the first lap of a race included the distance attained with the start, and during each subsequent lap there was a pushoff from the side of the pool after the turn. Attempts were made to apply correction factors using the average time between the starting signal and the swimmer's head passing a mark 7.5 m from the start varied between 2.31 to 2.59 s for freestyle events from 100 to 500 yd. Using these factors

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to correct the velocity of the first length of the races yielded estimated swimming velocities which did not have a consistent relationship with the speeds of the subsequent laps. Thayer and Hay (12) also gave values for the average time to traverse the last 2–3 m of each lap and the first 6.5 m of the next length. These values were called the "turning time and distance." Correcting the calculated distance per stroke for the turns uniformly decreased these values by approximately 5%. Analysis of East's data (8) indicated that when measuring the swimming velocity of a 100-m race these inherent errors occur throughout in a systematic fashion and do not greatly influence comparisons of different groups of swimmers. Therefore, it was decided not to attempt a correction of the data with these uniform factors.

The composition of the groups of swimmers was determined mostly by the "entry time" for each event. Each swimmer qualified for the competition by swimming the race in a time which was equal to or less than the "entry time." These times were different for each year of the study, but they limited the participants to those whose performance could be considered elite in terms of all the other swimmers in the country. In 1976 there were 623 participants in the 10 events studied, and in 1984 there were 941. There was about equal participation of men and women in both years. The 200-m and 400-m individual medley events were not included in the study. No observations of these races were made in 1976, and therefore no comparisons were available.

In 1976 we had only three observers, and 74% of the swims were evaluated. The stroke rates of swimmers in lanes 1 and 8 were not measured. According to the placement of swimmers in the different events, these lanes were occupied by the slowest competitors in each heat. However, there was some compensation for this bias of the data as the first preliminary heats of each event incuded the swimmers with the slower "entry times." In the current investigation we measured every length of every swim. Despite these differences in populations and in the proportion of the swimmers studied, the distributions of mean velocity for each swimmer as compared to the winner's velocity in each race was almost the same for each year (Fig. 1). On this basis it was felt that comparisons of the swimmers in 1984 with those in 1976 probably reflected changes in the techniques of swimming.

All of the results are depicted by plotting the velocity as a function of the stroke rate. As the distance per stroke is the ratio of the velocity to the stroke rate, isopleths indicating different distances can also be constructed (Fig. 2).

The relationships between velocity and stroke rate have previously been illustrated as a stroke rate-velocity curves for the different competitive strokes (2). One such curve is shown in Figure 2 and represents previously reported data of two outstanding front crawl swimmers (2). It was observed that as the stroke rate was increased from 20 to 30 cycles·min^{-1}, faster speed was also associated with an increase in the distance obtained with each stroke cycle. Further increases in velocity were characterized by increasing stroke rate and decreasing distance per stroke. A maximal velocity

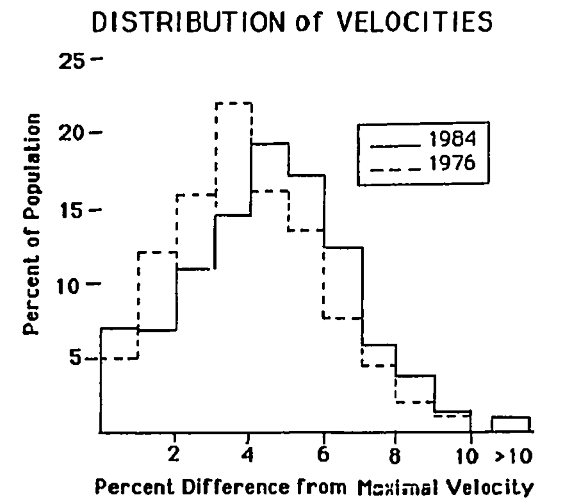

Figure 1—Distribution curves of velocities expressed as a percentage of difference from the velocity of the fastest swimmer in the preliminaries of each event for men and women are shown for 461 swims in 1976 and 941 swims in 1984.

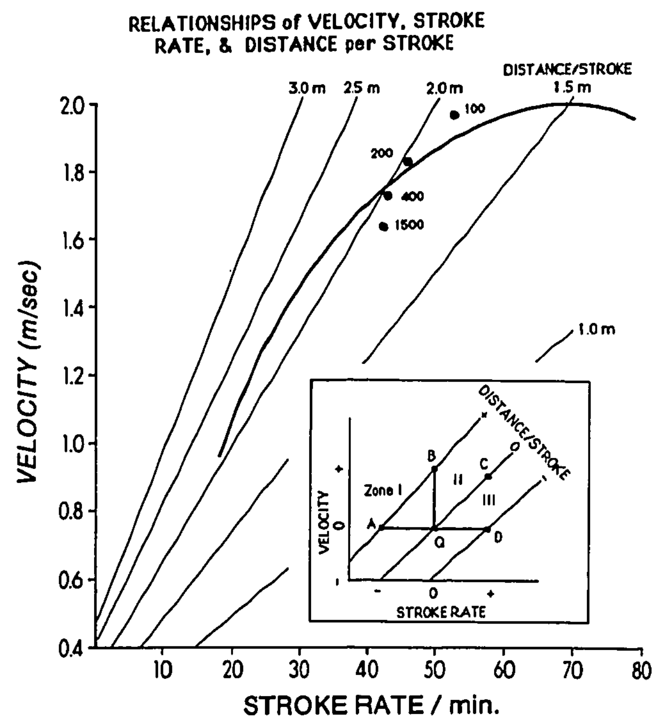

Figure 2—The curve shows the stroke rate velocity relationship of two elite male freestyle swimmers reported previously (2). The dots labeled 100, 200, 400, and 1500 indicate the mean velocity of the 8 finalists in the four men's freestyle races in 1984. The inset indicates the theoretical changes of stroke rate and distance per stroke which would result in an increase of velocity. See text for additional explanation.

was achieved by a unique combination of stroke rate and distance per stroke. Further increases of stroke rate resulted in decreases of velocity.

Also shown in Figure 2 are points indicating the average data from four men's freestyle races swum by the eight finalists in the 1984 competition. As indicated previously (2), the results from the 100-, 200-, and 400-m events tended to lie along the stroke rate-velocity curve of the two fast swimmers. Therefore, it is possible to view the results in the four different stroke styles in terms of stroke rate-velocity curves which illustrate the characteristics of different groups of swimmers.

As indicated in the inset in Figure 2, differences in velocities between groups of swimmers can be represented by vectors which have different lengths and directions. In zone I, bounded by AQB, increased velocity is accounted for by increased distance per stroke and decreased stroke rate. Increased speed can also be obtained by increased distance per stroke with no change in stroke rate, i.e., QB. Increased velocity can result from both an increased stroke rate and increased distance per stroke, in which case the vector would lie in zone II bounded by BQC. A fourth possibility is defined by increasing stroke rate without changing the distance per stroke, i.e., QC. The fifth relationship which may account for increased velocity includes increasing stroke rate and decreasing, to a limited extent, the distance per stroke, as illustrated in Zone III, which is limited by CQD. This graphical representation has been employed to illustrate the results.

RESULTS

The basic relationships between velocity and stroke rate in all four types of swimming events were the same in 1984 as observed in 1976 (2). In the freestyle events for men, which were swum using the front crawl stroke, the increased velocity of the shorter as compared to the longer races was associated with a decrease of the distance per stroke and an increase of the stroke rate (Fig. 3). For women the increased velocity was accounted for by the increase of stroke rate with a relatively constant distance per stroke. In the freestyle events women's stroke rates were about 10% greater than those for men. In the other 3 stroke styles stroke rates of the men and the women were not significantly different.

In the backstroke (Fig. 4) and in the breaststroke (Fig. 5), the faster speeds of the 100-m events as compared to the 200-m distances were also characterized by a faster stroke rate and a shorter distance per stroke for both men and women. In contrast, the faster velocity of the 100-m butterfly race was related to both a faster stroke rate and a greater distance per stroke than used for the 200-m distance (Fig. 6). This aberration was previously reported (2), and it was suggested that this

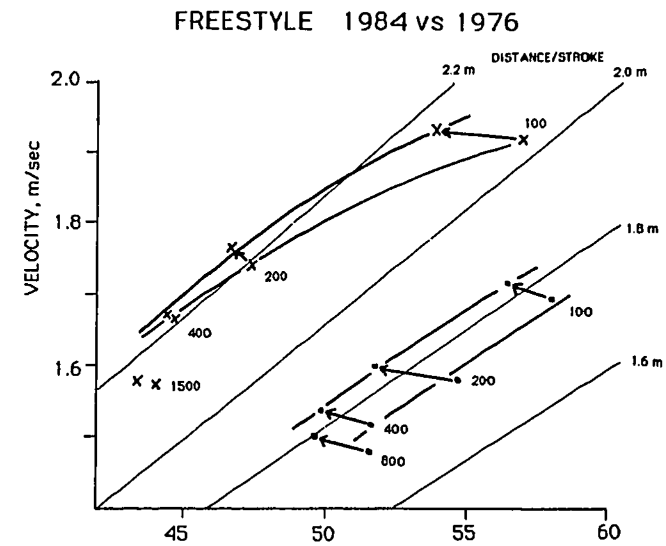

Figure 3—The average stroke rates and velocities of the freestyle events for men (×) and women (●) are shown for 1984 and 1976. The numbers near the sets of data points indicate the length of the race in m. In the events in which there was a significant increase of the velocity between the 2 yr the vectors indicate the manner in which the change occurred. Lines connecting the events of different distances represent small portions of a stroke rate-velocity curves which characterize these swimmers.

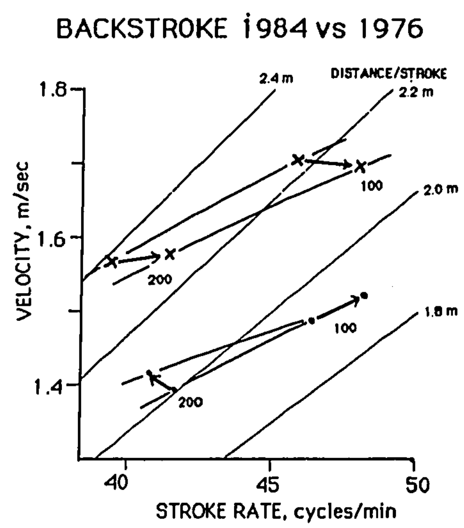

Figure 4—The average stroke rates and velocities of the backstroke events. See legend of Figure 3 for explanation.

choice of shorter rather than longer distances per stroke as in other stroke styles may be related to local muscle fatigue, which is particularly severe in this stroke pattern. The mean values and their statistical limits are given in Tables 1 and 2.

Comparisons between 1976 and 1984 indicated that velocities of 9 out of the 10 races for women were significantly increased (Table 1). Only 3 of the 10 men's events showed improvement (Table 2). The average speed for the women was 1.5% and that of the men was 0.6% greater in 1984 than in 1976. For the women the increased velocity was accounted for by an increased

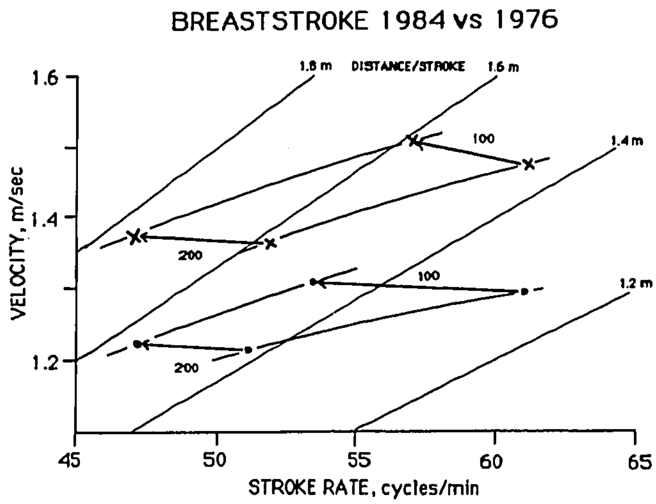

Figure 5—The average stroke rates and velocities of the breaststroke events. See legend of Figure 3 for explanation.

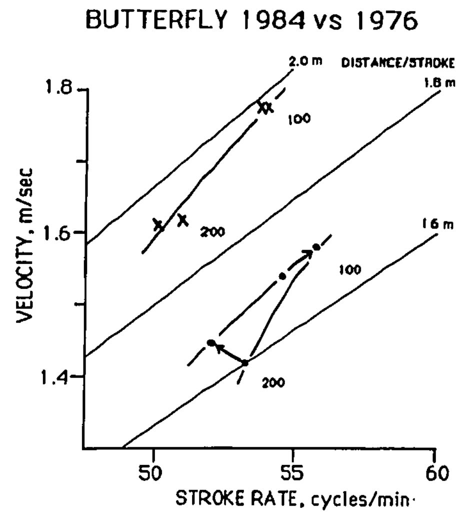

Figure 6—Average stroke rates and velocities of the butterfly events. See legend of Figure 3 for explanation.

TABLE 1. Relationships of velocity (VEL), stroke rate (SR), and distance per stroke ($D \cdot ST^{-1}$), at the 1976 and 1984 U.S. Olympic Trials.

	Women							
	1976 Trials				1984 Trials			
Event	VEL ($m \cdot s^{-1}$)	SR (cycles·min^{-1})	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N	VEL ($m \cdot s^{-1}$)	SR (cycles·min^{-1})	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N
FR†, 100 m	1.693 ± 0.005	58.1 ± 1.1	1.76 ± 0.03	27	1.711 ± 0.004*	56.4 ± 0.6	1.83 ± 0.02*	69
FR, 200 m	1.579 ± 0.006	54.7 ± 1.1	1.75 ± 0.04	20	1.597 ± 0.004*	51.7 ± 0.7*	1.87 ± 0.03*	55
FR, 400 m	1.519 ± 0.005	51.6 ± 1.0	1.78 ± 0.03	22	1.533 ± 0.005*	49.8 ± 0.6*	1.86 ± 0.02*	43
FR, 800 m	1.481 ± 0.006	51.5 ± 0.6	1.73 ± 0.02	18	1.497 ± 0.005*	49.6 ± 0.6*	1.82 ± 0.02	43
BA, 100 m	1.489 ± 0.005	46.3 ± 0.7	1.94 ± 0.03	21	1.521 ± 0.005*	48.2 ± 0.9*	1.92 ± 0.03	42
BA, 200 m	1.392 ± 0.007	41.7 ± 0.6	2.01 ± 0.03	22	1.415 ± 0.008*	40.8 ± 0.5	2.09 ± 0.03*	42
BR, 100 m	1.294 ± 0.005	61.1 ± 1.3	1.28 ± 0.02	22	1.309 ± 0.002*	53.4 ± 0.7*	1.48 ± 0.02*	60
BR, 200 m	1.213 ± 0.006	51.2 ± 0.9	1.43 ± 0.03	16	1.223 ± 0.006	47.1 ± 0.7*	1.57 ± 0.03*	38
FL, 100 m	1.538 ± 0.005	54.5 ± 0.6	1.70 ± 0.02	36	1.584 ± 0.006*	55.6 ± 0.5*	1.71 ± 0.02	38
FL, 200 m	1.418 ± 0.005	53.2 ± 0.8	1.61 ± 0.03	32	1.446 ± 0.005*	51.9 ± 0.5*	1.68 ± 0.02*	43
				Total = 237				Total = 473

Values are mean ± SE.
* Indicates significant differences between 1976 and 1984, i.e., $P < 0.05$.
† FR indicates freestyle events; BA, backstroke; BR, breaststroke; and FL, butterfly.
N, number of swimmers observed.

TABLE 2. Relationships of velocity (VEL), stroke rate (SR), and distance per stroke ($D \cdot ST^{-1}$) at the 1976 and 1984 U.S. Olympic Trials.

	Men							
	1976 Trials				1984 Trials			
Event	VEL ($m \cdot s^{-1}$)	SR (cycles·min^{-1})	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N	VEL ($m \cdot s^{-1}$)	SR (cycles·min^{-1})	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N
FR†, 100 m	1.915 ± 0.006	57.0 ± 0.9	2.03 ± 0.03	24	1.930 ± 0.005*	53.9 ± 0.06*	2.16 ± 0.03*	50
FR 200, m	1.743 ± 0.008	46.4 ± 0.9	2.27 ± 0.04	19	1.762 ± 0.005*	46.6 ± 0.5	2.29 ± 0.03	56
FR, 400 m	1.670 ± 0.007	44.4 ± 1.1	2.28 ± 0.06	18	1.665 ± 0.005	44.6 ± 0.5	2.26 ± 0.03	47
FR, 1500 m	1.570 ± 0.007	44.1 ± 0.6	2.14 ± 0.03	28	1.576 ± 0.004	43.4 ± 0.4	2.19 ± 0.02	38
BA, 100 m	1.703 ± 0.007	45.8 ± 0.7	2.24 ± 0.03	18	1.699 ± 0.005	47.2 ± 0.5*	2.17 ± 0.02*	49
BA, 200 m	1.565 ± 0.006	39.4 ± 0.5	2.39 ± 0.03	24	1.575 ± 0.005	41.5 ± 0.4*	2.29 ± 0.02*	48
BR, 100 m	1.476 ± 0.006	61.2 ± 0.8	1.45 ± 0.02	28	1.512 ± 0.6*	57.1 ± 0.8*	1.60 ± 0.02*	44
BR, 200 m	1.364 ± 0.009	51.9 ± 1.2	1.59 ± 0.04	16	1.377 ± 0.005	47.1 ± 0.7*	1.77 ± 0.03*	50
FL, 100 m	1.775 ± 0.004	53.6 ± 0.5	1.99 ± 0.02	28	1.777 ± 0.005	53.8 ± 0.4	1.99 ± 0.02	47
FL, 200 m	1.618 ± 0.007	50.9 ± 0.5	1.91 ± 0.02	21	1.610 ± 0.006	50.0 ± 0.5	1.94 ± 0.02	39
				Total = 224				Total = 468

Values are mean ± SE.
* Indicates significant differences between 1976 and 1984, i.e., $P < 0.05$.
† FR indicates freestyle events; BA, backstroke; BR, breaststroke; and FL, butterfly.
N, number of swimmers observed.

distance per stroke and a decreased stroke rate in 7 events, whereas in the 100-m backstroke and the 100-m butterfly the increased velocity was associated with an increased stroke rate and no change in the distance per stroke.

For men the 100-m freestyle and the 100-m breaststroke races were swum faster in 1984 than in 1976, and these differences were also related to an increased distance per stroke and a decrease of the stroke rate (Table 2). Although the 200-m freestyle event was also faster, neither the increased distance per stroke nor the decreased stroke rate were significantly different in 1984 as compared to 1976.

Even though there was little improvement in the times of some events, there were significant changes in the manner in which they were swum. The velocities of the men's 100-m and 200-m backstroke events were about the same in both years. However, the stroke rates were increased, and the distances per stroke were less in 1984 than in 1976 (Fig. 5). The most dramatic changes were seen in the breaststroke. In 1984 all men and women's races were swum with much slower stroke rates and much longer distances per stroke than in 1975, but the velocities were improved only for the 100-m races.

Another use of the 1984 data provided a comparison of the characteristics of the swimmers whose velocities in the preliminary races were between 3 and 7% slower (93–97% group) than the average of the 8 swimmers in the finals of each event (Tables 3 and 4). The data selection was designed to create a subgroup whose velocities had a uniform relationship to the fastest swimmers in each event. The distribution of times in the different preliminary events varied. In some, which were very competitive, there were many swimmers whose times were much closer to those of the finalists than in other events (Table 5). The average velocity of the 93–97% group was 4.6% slower than the finalists (SD, 0.4%). The 93–97% group represented 57% of all of the preliminary swims for women and 50% for men.

TABLE 3. Relationships of velocity (VEL), stroke rate (SR), and distance per stroke ($D \cdot ST^{-1}$) at 1984 U.S. Olympic Trials for the finals and for the preliminary races in which the swimmers' velocities were between 93 and 97% those of the average finalists' times.

	Women							
	Finalists				Preliminaries (93–97% velocity)			
	VEL ($m \cdot sec^{-1}$)	SR ($cycles \cdot min^{-1}$)	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N	VEL ($m \cdot s^{-1}$)	SR ($cycles \cdot min^{-1}$)	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N
FR, 100 m	1.770 ± 0.004	54.7 ± 1.2	1.95 ± 0.04	8	1.695 ± 0.002*	56.8 ± 0.8*	1.80 ± 0.02*	47
FR, 200 m	1.653 ± 0.004	51.0 ± 1.6	1.96 ± 0.06	8	1.579 ± 0.002*	51.4 ± 0.9	1.86 ± 0.04*	32
FR, 400 m	1.589 ± 0.006	51.6 ± 1.2	1.85 ± 0.04	8	1.517 ± 0.003*	49.4 ± 0.7*	1.85 ± 0.03	29
FR, 800 m	1.556 ± 0.006	51.4 ± 0.9	1.82 ± 0.03	8	1.480 ± 0.003*	49.6 ± 0.8*	1.80 ± 0.03	26
BA, 100 m	1.579 ± 0.005	46.6 ± 0.8	2.04 ± 0.03	8	1.507 ± 0.003*	48.5 ± 1.4	1.89 ± 0.04*	27
BA, 200 m	1.472 ± 0.003	41.5 ± 1.5	2.15 ± 0.07	8	1.396 ± 0.003*	40.5 ± 0.8	2.08 ± 0.04	18
BR, 100 m	1.378 ± 0.008	52.2 ± 1.1	1.59 ± 0.03	8	1.307 ± 0.002*	53.8 ± 0.8*	1.47 ± 0.02*	32
BR, 200 m	1.282 ± 0.010	47.0 ± 1.2	1.65 ± 0.05	7	1.215 ± 0.003*	47.6 ± 0.8	1.54 ± 0.03	20
FL, 100 m	1.616 ± 0.003	55.8 ± 1.0	1.75 ± 0.06	8	1.555 ± 0.003*	55.3 ± 0.7	1.69 ± 0.02	15
FL, 200 m	1.496 ± 0.012	52.4 ± 1.2	1.72 ± 0.05	8	1.427 ± 0.002*	51.7 ± 0.6	1.66 ± 0.02	28
								Total = 271

Values are mean ± SE.
* Indicates significant differences between finalists and those in the preliminaries whose velocities were 93–97% of the finalists' speeds, i.e., $P < 0.05$.

TABLE 4. Relationships of velocity (VEL), stroke rate (SR), and distance per stroke ($D \cdot ST^{-1}$) at 1984 U.S. Olympic Trials for the finals and for the preliminary races in which the swimmers' velocities were between 93 and 97% those of the average finalists' times.

	Men							
	Finalists				Preliminaries (93–97% velocity)			
	VEL ($m \cdot /s^{1}$)	SR ($cycles \cdot min^{-1}$)	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N	VEL ($m \cdot s^{-1}$)	SR ($cycles \cdot min^{-1}$)	$D \cdot ST^{-1}$ ($m \cdot ST^{-1}$)	N
FR, 100 m	1.980 ± 0.008	53.1 ± 1.3	2.24 ± 0.05	8	1.899 ± 0.003*	54.7 ± 0.6*	2.09 ± 0.03*	22
FR, 200 m	1.820 ± 0.005	46.6 ± 0.8	2.35 ± 0.04	8	1.737 ± 0.003*	47.1 ± 0.7	2.23 ± 0.03*	28
FR, 400 m	1.717 ± 0.004	43.6 ± 1.1	2.37 ± 0.05	8	1.642 ± 0.003*	45.8 ± 0.7*	2.16 ± 0.03*	20
FR, 1500 m	1.631 ± 0.008	42.3 ± 0.9	2.32 ± 0.05	8	1.558 ± 0.002*	44.0 ± 0.7*	2.14 ± 0.03*	22
BA, 100 m	1.761 ± 0.008	47.9 ± 0.8	2.21 ± 0.03	8	1.684 ± 0.003*	47.1 ± 0.6	2.15 ± 0.03	27
BA, 200 m	1.624 ± 0.010	42.4 ± 0.6	2.30 ± 0.03	8	1.553 ± 0.003*	41.5 ± 0.7	2.26 ± 0.04	22
BR, 100 m	1.574 ± 0.009	56.4 ± 1.6	1.69 ± 0.05	8	1.499 ± 0.002*	59.3 ± 1.0*	1.53 ± 0.03*	19
BR, 200 m	1.443 ± 0.003	45.1 ± 1.1	1.93 ± 0.05	8	1.373 ± 0.003*	47.9 ± 0.8*	1.71 ± 0.03*	35
FL, 100 m	1.828 ± 0.009	53.7 ± 0.9	2.05 ± 0.04	8	1.748 ± 0.004*	53.6 ± 0.5	1.96 ± 0.02*	16
FL, 200 m	1.665 ± 0.006	50.4 ± 0.5	1.98 ± 0.02	8	1.589 ± 0.004*	50.4 ± 0.8	1.90 ± 0.03*	22
								Total = 233

Values are mean ± SE.
* Indicates significant differences between finalists and those in the preliminaries who were 93–97% of the finalists' speeds, i.e., $P < 0.05$.

TABLE 5. Percentage of difference** in velocity, stroke rate, and distance per stroke of 93-97% group from the finalists.

	Women			Men		
	VEL (m·s⁻¹)	SR (cycles·min⁻¹)	D·ST⁻¹ (m·ST⁻¹)	VEL (m·s⁻¹)	SR (cycles·min⁻¹)	D·ST⁻¹ (m·ST⁻¹)
FR, 100 m	−4.3	3.9 ± 1.5*	−7.3 ± 1.3*	−4.1	2.9 ± 1.3*	−6.9 ± 1.2*
FR, 200 m	−4.5	0.8 ± 0.9	−4.9 ± 1.8*	−4.6	0.9 ± 1.5	−5.1 ± 1.4*
FR, 400 m	−4.5	−4.4 ± 1.4*	0 ± 1.4	−4.4	4.9 ± 1.6*	−8.9 ± 1.3*
FR, 800 m†	−4.8	−3.5 ± 1.3*	−1.0 ± 1.3	−4.5	3.9 ± 1.5*	−7.9 ± 1.4*
FR, 1500 m						
BA, 100 m	−4.6	4.2 ± 3.1	−7.1 ± 2.0*	−4.4	−1.5 ± 1.3	−2.6 ± 1.3*
BA, 200 m	−5.1	−2.5 ± 2.0	−2.9 ± 1.8	−4.3	−2.2 ± 1.6	−1.7 ± 1.7
BR, 100 m	−5.2	3.1 ± 1.5*	−7.7 ± 1.4*	−4.8	5.3 ± 1.9*	−9.5 ± 1.6*
BR, 200 m	−5.3	1.3 ± 1.6	−6.4 ± 1.8*	−4.8	6.1 ± 1.8*	−9.8 ± 1.5*
FL, 100 m	−3.8	−0.9 ± 1.2	−3.1 ± 1.3*	−4.4	−0.2 ± 1.0	−4.4 ± 1.0*
FL, 200 m	−4.6	−1.3 ± 1.2	−3.4 ± 1.1*	−4.5	−0.1 ± 1.6	−4.0 ± 1.4*
Average	−4.7			−4.5		

Values are mean ± SE.
* Indicates significant differences between finalists and those in the preliminaries whose velocities were 93-97% of the finalists' speeds, i.e., $P < 0.05$.
** Percentage of difference = [(value for 93-97% group-value for finalists)/value for finalists] × 100.
† FR, 800 m and FR, 1500 m indicate events for women and men, respectively.

Having defined these two groups, i.e., the finalists and the 93–97% group, it was then possible to examine the differences of stroke rate and/or distance per stroke which might account for the differences in speed.

In each type of competitive stroke, the lines connecting the events of different distances indicate that the stroke rate-velocity relationships were more favorable for the finalists than for the 93–97% group. In 9 of the 10 men's events and 7 out of 10 women's events the finalists had greater distances per stroke than did the 93–97% group (Table 5). In all of the men's freestyle events and the women's 100-m and 200-m freestyle the vectors which indicated the differences between the finalists and the 93–97% group all tend to lie in Zone I (Fig. 7 and Tables 3 and 4). This observation indicated that the finalists used slower stroke rates and achieved greater distances per stroke than those in the 93–97% group. However, in the 400-m and 800-m women's events the finalists were faster only by virtue of their faster stroke rates. There were no differences in the distances per stroke.

In contrast, 3 out of 4 of the backstroke events had the vectors which indicated that the finalists used faster stroke rates and also had greater distances per stroke than did the 93–97% group (Fig. 8). The exception to this pattern was seen in the 100-m women's backstroke race in which the finalists had slower stroke rates and longer distances per stroke than did the 93–97% group.

In 3 out of 4 breaststroke events the finalists had greater distances per stroke and slower stroke rates than did the 93–97% group. Although the finalists in the 200-m breaststroke for women also had a greater distance per stroke than did the 93–97% group, there was no significant difference in stroke rate between the two groups (Fig. 9).

The butterfly events were somewhat different from the others. In all of the four races, the finalists could be

FREESTYLE finals vs 93-97% group

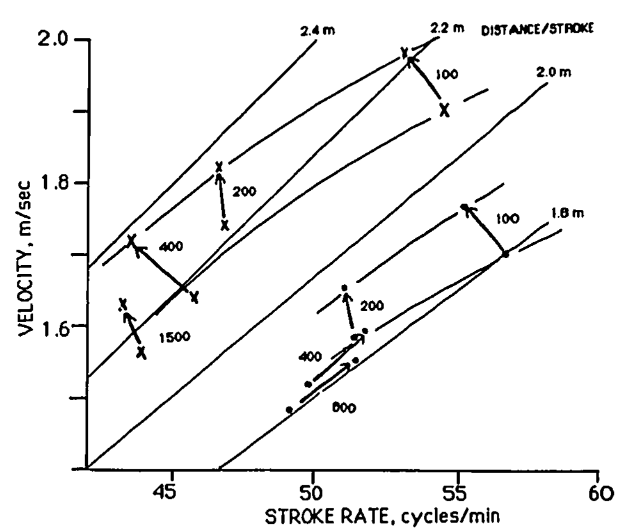

Figure 7—Average stroke rates and velocities of the freestyle events are shown for men (×) and women (●) for the 8 finalists and for the 93–97% groups in the preliminaries. The numbers by each set of data indicate the distance of the race. The vectors connect the data points for the 93–97% group to those of the respective finalists data and indicate the type of differences which occurred. See text for further explanation.

distinguished from the 93–97% group almost completely by their longer distance per stroke (Fig. 10).

In addition to these differences between the finalists and the 93–97% group it was also possible in some events to identify differences in the profile of velocity during a race. The differences in velocities between the finalists and the 93–97% group tended to become greater as the race progressed. In all of the men's 100-m events and all but the 100-m butterfly for women the velocity difference between the finalists and the 93–97% group averaged 3.9% for the first 50 m and 4.8% for the second 50 m. In the women's 100-m butterfly race the finalists were 5.5% faster than the 93–97%

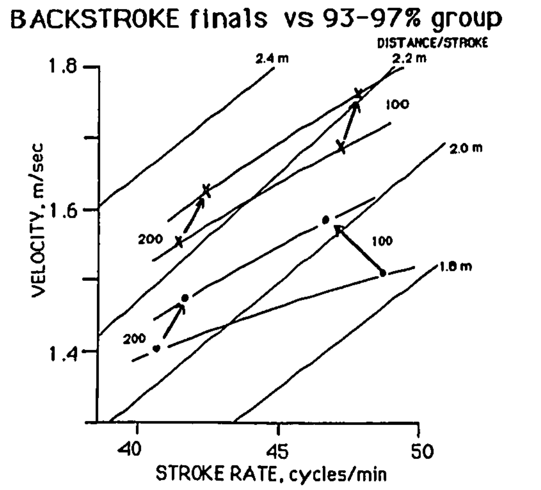

Figure 8—The average stroke rates and velocities of the backstroke events for finalists and the 93-97% groups. See legend of Figure 7 for explanation.

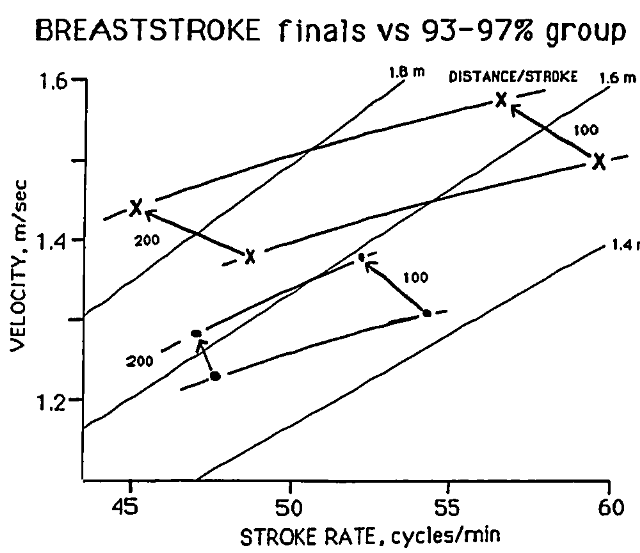

Figure 9—The average strokes rates and velocities of the breaststroke events for finalists and the 93-97% groups. See legend of Figure 7 for explanation.

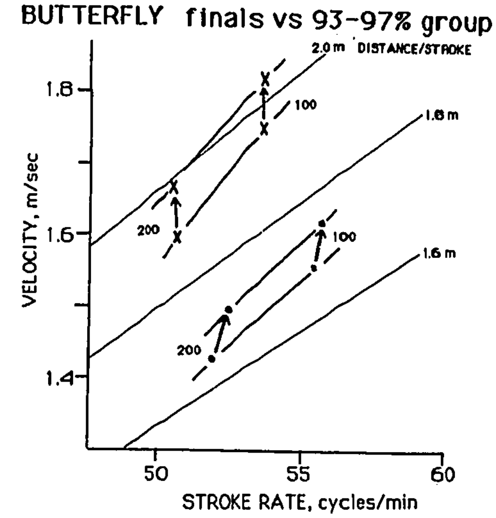

Figure 10—The average stroke rates and velocities of the butterfly events for finalists and the 93-97% groups. See legend of Figure 7 for explanation.

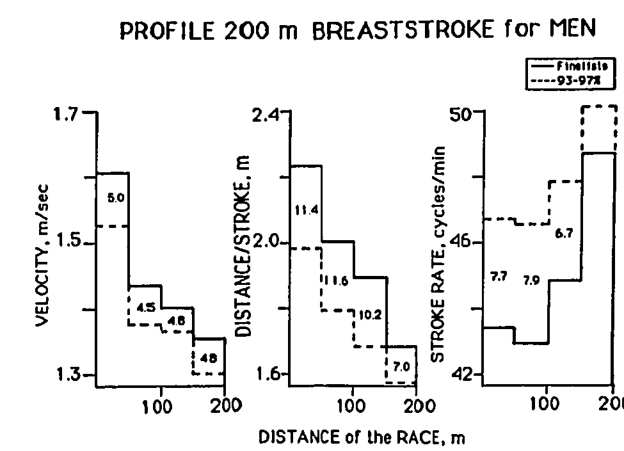

Figure 11—Changes in velocity, distance per stroke, and stroke rate for the finalists and the 93-97% group in the men's 200-m breaststroke event. The numbers between the two curves indicate the percentage of difference between the two groups when the difference was statistically significant, i.e., $P < 0.05$.

group in the first lap but only 2.6% faster in the second lap. In the 200-m events the mean velocity difference was 3.8% in the first half of the race and 5.5% in the second half.

In the 100-m races it was not possible to account for these velocity profiles in terms of statistically significant differences in the changes of stroke rate or distances per stroke between the finalists and the 93-97% groups. However, in the 200-m events two types of profiles were noted. In all of these races there was a decrease in the distance per stroke throughout the race. In some races the finalists compensated for the decrease in distance per stroke by increasing stroke rate, but the 93-97% group did not. In others the finalists' faster velocities were accounted for solely by their maintaining greater distances per stroke throughout the race.

The first pattern is illustrated by the men's 200-m breaststroke event. All of the swimmers experienced large decrements in distance per stroke during the race (Fig. 11), but the finalists compensated by increasing the stroke rate much more than did the 93-97% group. The 200-m backstroke races for both men and women showed this same profile.

The men's 200-m freestyle illustrates the second type of profile. The finalists maintained the distance per stroke better than the 93-97% group (Fig. 12). In the last lap the 93-97% group had a significantly greater stroke rate than the finalists, but as the distance per stroke had decreased, the velocity differences between the two groups was maintained. This type of profile was also noted in the men's 200-m butterfly and in all the women's 200-m events except the backstroke.

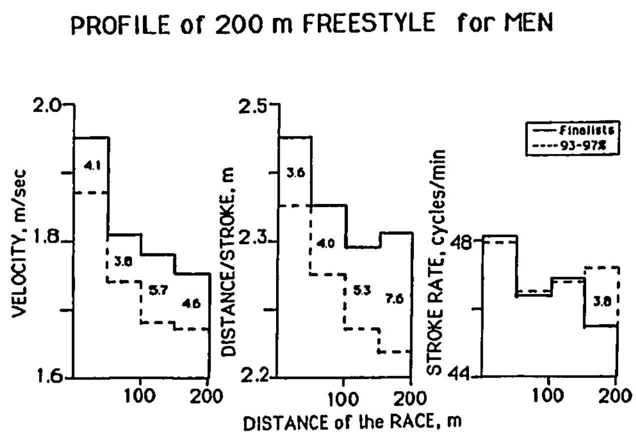

Figure 12—Changes in velocity, distance per stroke, and stroke rate for the finalists and the 93–97% group in the men's 200-m freestyle event.

The 400-m freestyle races provided more data to define the profiles of the races. In both men's and women's races the velocity of the 93–97% group decreased progressively throughout the races until the last 50 m (Fig. 13). The women finalists maintained their speed from 100 to 350 m somewhat better than did the 93–97% group. As the stroke rates were not different between the two groups at any point in the race, the superior ability of the women finalists was attributed to their greater distance per stroke. In the men's event the finalists maintained speed from 100 to 300 m and actually increased velocity in the last 100 m. The distance per stroke decreased for both groups throughout. However, the finalists maintained and then increased velocity by increasing stroke rate in the last half of the race.

In the 800-m freestyle for women the difference in velocity between the finalists and the 93–97% group was also explained by stroke rate. The finalists maintained their velocity better than did the 93–97% group from 100 to 700 m (Fig. 14). The distances per stroke of the two groups were not significantly different, and the finalists' faster velocities were due to progressively increasing stroke rate from 400 m to the end of the race.

In the men's 1500-m freestyle the finalists had a significantly greater distance per stroke and a slightly lower stroke rate than did the 93–97% group (Fig. 15). These differences were simply maintained throughout the race. From 100 to 700 m the velocity of the 93–97% group decreased 0.03 $m \cdot s^{-1}$, while that of the finalists decreased 0.01 $m \cdot s^{-1}$. Otherwise, the changes in distance per stroke and stroke rate from the beginning to the end of the race were very similar.

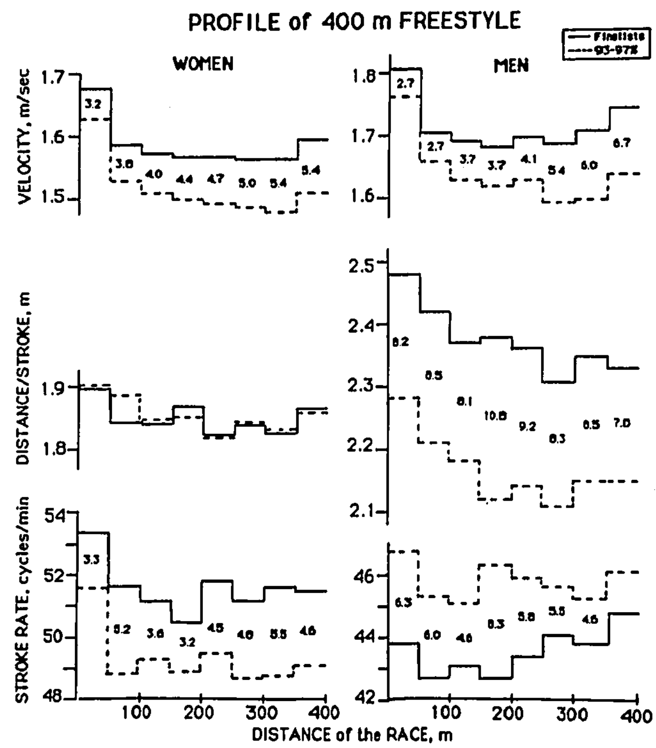

Figure 13—Changes in velocity, distance per stroke, and stroke rate for the finalists and the 93–97% groups for the women's and the men's 400-m freestyle events. See legend of Figure 11 for additional explanation.

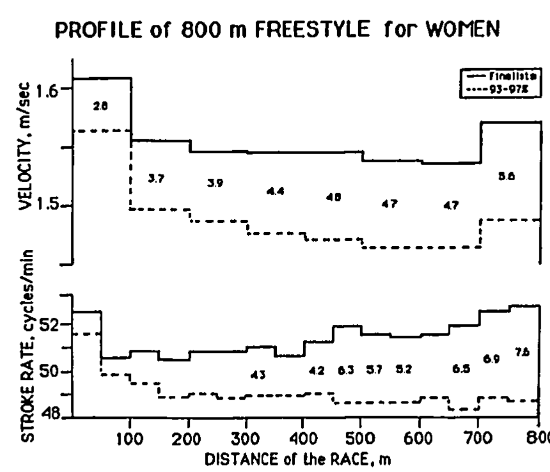

Figure 14—Changes in velocity and stroke rate for the finalists and the 93–97% group for the women's 800-m freestyle event. Distances per stroke are not shown, as there were no significant differences between the two groups. See legend of Figure 11 for additional explanation.

DISCUSSION

As indicated by Hay and Guimaraes (9), "it is surprising that there have been only a mere handful of studies concerned with obtaining a clear understanding of the relationships among stroke length, stroke frequency, and time." The first such study was that of East, who analyzed films from the men and women's 100-yd (100.6-m) events in all 4 stroke styles at the 1969 New Zealand Amateur Swimming Championships (8). There were 48 male and 51 female competitors, and except for the women's backstroke, in which there were 3 contestants, the other events included from

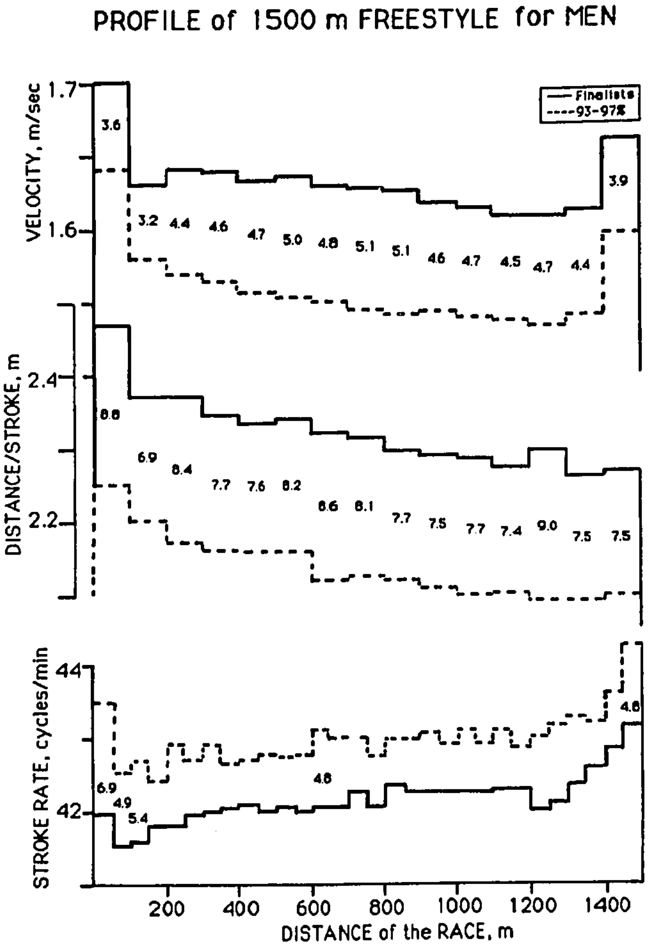

Figure 15—Changes in velocity, distance per stroke, and stroke rate for the finalists and the 93–97% group for the men's 1500 m freestyle. See legend of Figure 11 for additional explanation.

10 to 18 swimmers. The mean velocity of these swimmers was 17% less than those reported above for the 1984 U.S. Olympic Trials. The only statistically significant difference in stroke rates between the two studies was in the women's freestyle, in which the New Zealand swimmers' mean rate was 9% faster than that of the U.S. swimmers. In all of the races the shorter distances per stroke of East's study accounted for the slower velocities.

Hay and Guimaraes (9) filmed the University of Iowa men's swimming team's races throughout the season and reported their analysis of the 200-yd freestyle events. They found that the decline of the velocity during these races was almost completely accounted for by decreasing distance per stroke. The stroke rate stayed "essentially constant as the race progressed." They also suggested that "improvements in velocity over the course of a season were almost exclusively due to corresponding improvements of stroke length" in the later parts of the race.

The results of the current study also indicate the importance of the distance per stroke in determining a swimmer's velocity. Improvements in velocity between 1976 and 1984 were attributable to increased distance per stroke and decreased stroke rate in 9 out of 11 events. The faster velocities of the finalists as compared to the 93–97% group were accounted for by greater distances per stroke in 9 out of the 10 men's events and in 7 out of the 10 women's events. The profile of some races such as the 200-m freestyle race for men also agreed with the findings of Hay and Guimaraes (9). The declining velocity during the race was due entirely to decreasing distance per stroke (Fig. 12). Although it is evident that traveling a long distance per stroke is an important attribute of skilled swimmers, stroke rate cannot be neglected.

The women's 100-m backstroke and butterfly events were faster in 1984 than in 1976 simply because the swimmers used faster stroke rates. The superior velocities of the finalists in the women's 400-m and 800-m freestyle events was due entirely to stroke rate. In the men's 200-m breaststroke the finalists attained greater distances per stroke than did the 93–97% group, but in the last two laps of the race the finalists compensated for decreasing distance per stroke by increasing stroke rate more than the 93–97% group (Fig. 11). Similar patterns were noted in the men's and women's 200-m backstroke. In the men's 400-m freestyle event the distinguishing feature of the finalists was their ability to increase velocity in the last 100 m of the race by increasing stroke rate.

As shown in Figure 2 the relationships between velocity, stroke rate, and distance per stroke cycle can be described by stroke rate-velocity curves. We have previously shown that improvements in performance are associated with changes of an individual's stroke rate-velocity curve (3,4). Through training these swimmers achieved a greater velocity for a given stroke rate and also had faster maximal velocities during short 8–10-m sprints. In Figures 3–10 we have suggested what small portions of these swimmers' stroke rate-velocity curves might look like for the four competitive stroke styles. Improvements in 1984 as compared to 1976 are characterized by a shift of the curve up and to the left on these plots (Figs. 3-6). In general, the stroke rate-velocity curves for the finalists were displaced up and to the left of those for the 93–97% group (Figs. 7–10). It is apparent that stroke rate-velocity curves are applicable to groups of swimmers as well as to individuals.

However, this may be somewhat misleading, as we know that individual swimmers do not swim their races "on the curve." We have determined the stroke rate-velocity curves for many swimmers by measuring the velocities in repeated swims using a range of stroke rates from 20 to 70 cycles$\cdot$min^{-1} (4). We also measured their velocities and stroke rates and calculated distance per stroke during actual competiton. The combination of stroke rate and distance per stroke during competition always fell under an individual's curve. As the race progressed the decrease of velocity was not represented by progressing "down the curve" but by points farther away from the curve. These observations indicate that as a swimmer fatigues during a race, there is a loss of distance per stroke. This is probably related to a decreasing ability to develop the force necessary to overcome resistance to forward movement. There is also the possibility that some swimmers' losses in distance per stroke may also be related to increased drag. As the swimmers fatigue, they may pay less attention to body alignment, which is important in minimizing drag (6,11).

Changes in the times of elite swimmers between 1976 and 1984 and the differences between the best of these swimmers and the slightly less skilled have been interpreted in terms of the biomechanics of swimming. It is also possible that differences in velocity might be related to differences in maximal energy production (7,10,11). In the men's and women's freestyle events the velocities of the finalists were 4.5% greater than those of the 93–97% group. The relationships between energy costs and velocity are not linear. If the efficiency of swimming was the same in both groups, it was estimated that the energy costs of the finalists would be 10.5% greater than those of the 93–97% group. It seems unlikely that the finalists' capacity for energy production would be 10% greater than that of the 93–97% group, which was also highly trained and skilled. As the efficiency of swimming is in the range of 5 to 8%, it seems more reasonable to propose that biomechanical factors which affect active body drag and/or the development of propulsive force are largely responsible for the observed differences.

For the past 20 yr training for swimming has been characterized by long hours spent swimming long distances. Such programs are aimed at increasing the swimmers' capacities to produce energy. It is suggested that training programs which emphasize improving the biomechanics of swimming and using these changes during competition might be a better use of time in the pool.

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