ISSN: 0747-5994
Vol. 14 Fall 2000

THE JOURNAL OF SWIMMING RESEARCH

CONTENTS

Fig.5

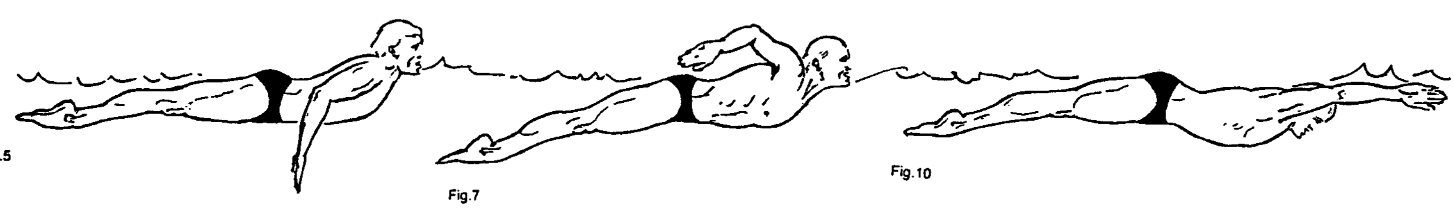

Fig.7

Fig.10

A publication of the ASCA in cooperation with the USA Swimming Sports Medicine Committee

ASCA

J. Swimming Research
Vol. 14 (2000) 9-17

Training using the stroke frequency-velocity relationship to combine biomechanical and metabolic paradigms

BUDD TERMIN, M.S.* AND DAVID R. PENDERGAST, ED.D.**

Departments of Physiology and Biophysics** and Athletics* Center for Research and Education in Special Environments
University at Buffalo, Buffalo, NY 14214

Corresponding Author: Dr. David Pendergast
Department of Physiology and Biophysics
124 Sherman Hall
School of Medicine and Biomedical Sciences
University at Buffalo
3435 Main Street
Buffalo, NY 14214
Telephone: (716) 829-3830
e-mail: dpenderg@buffalo.edu

Abstract

Current conventional swim training tends to focus on long over-distance swimming, often in combination with dry-land strength training and a season ending taper. This study evaluated the effectiveness of a novel training regime incorporating high-velocity swimming exclusively, without dry-land training or taper. Twenty-two Division I swimmers who trained on the high-velocity program were followed over their four competitive seasons and their performances in the 100 yard and 200 yard freestyle were tracked and shown to improve 8-10% over this time. The improved performance of the high-velocity group was coincident with a 20% reduction in the energy cost of swimming which was associated with a shift of the stroke frequency-velocity relationship toward one in which the body traveled greater distances per stroke (16%), with an increased maximal stroke rate (8%). Maximal aerobic power (48%), anaerobic power (16%) and anaerobic capacity (35%) increased in these swimmers during the four years studied. Their swim velocities increased 31% for speeds that could be sustained aerobically and 27% for maximal speeds. All of these changes are substantially greater than what is reported in the literature for conventional swim training programs. It is concluded that a swimming program using high-velocity training and primarily based on the stroke rate-velocity relationship, can improve a collegiate swimmer's biomechanics and metabolism ultimately leading to enhanced swim performances without dry-land training, over-distance training or a taper.

Key words: oxygen consumption, lactic acid, swimming performance, stroke frequency biomechanical and metabolic swim training

ISSN: 0774-5994

Introduction

Success in competitive swimming is based upon the time required by an athlete to cover various distances in the water using one or a combination of strokes. If the starts and turns are ignored, then the time required to cover a given distance can be expressed as a velocity. The ability to achieve and maintain a velocity over the distance of a race is related to biomechanical and metabolic factors. Among the important biomechanical factors are stroke frequency (arm cycles/min) and the distance that the body travels per stroke (m/stroke). Previous studies have shown that there is a characteristic relationship between stroke rate and swim velocity (5,10,11). These investigators have also shown that faster swimmers swim with a greater distance per stroke at both slow and fast speeds, have a greater ability to shorten their stroke, and have a higher maximal stroke rate. Craig and colleagues have shown that elite swimmers swim shorter distances per stroke and slower stroke rates during all competitive events than they theoretically could (based on their individual stroke frequency-velocity relationship) (11). Hypothetically then, increasing either the distance per stroke or stroke rate or both, would improve swim performance.

The metabolic factors important in swim performance are a combination of aerobic (VO_2), and anaerobic (anaerobic glycolysis leading to lactic acid build-up and high-energy phosphate metabolism) (4). Although the rate of energy required is determined by body drag and net mechanical and propelling efficiency while swimming (12,28), it can be expressed as the sum of VO_2 and the rates of anaerobic glycolysis and high energy phosphate use. The relative contribution of these pathways is dependent upon the velocity and distance of the competitive event (4). The ability to achieve and maintain a velocity is dependent upon the rate of energy cost of swimming at that velocity, and developing and supporting the external power with muscular (24) and metabolic (3,4) power. A decrease in the energy cost of swimming by improved biomechanics and/or an increase in metabolic power through effective training should act to improve competitive swim performance.

Previous studies have described the energy cost of swimming and the metabolic pathways that provide energy in recreational and competitive swimmers (3,4,12,30,31) and have evaluated these factors before and after training (4,30,31). Relationships between the energy cost of swimming, distance per stroke, stroke rate and the velocity of swimming have been reported (30). It has not been demonstrated if, or by how much, the stroke frequency-velocity relationship or the energy cost-velocity relationship can be shifted in an individual swimmer with training. It has also not been demonstrated which type of training is optimal in this regard.

Arguably, over-distance swimming ranging from 60 - 80,000 yards or meters per week, is the conventional swim training since the late 1960s, 1970s and 1980s. It might be suggested that due to the long-distance, the speed of training may not be great enough to cause the adaptation(s) needed to swim at the competitive velocities. This over-distance training has the potential to result in chronic fatigue in many swimmers. Chronic fatigue may lead to a compromise in the immune system, mental stress, fatigue and caloric deficit (14,17,18,29).

A "taper" is often used with long-distance training to allow swimmers to recover prior to a championship event. (14,21). The taper improves performance about 3% (14,20,21); however, at least one report indicates collegiate swimmers training with this method improve less than 1% per year (9). Several questions can be raised about the effectiveness of long-distance programs. The chronic fatigue accompanying this type of training may compromise the swimmer's ability to perform during training as well as during meets. Recently, it has been recognized that most competitive swims are at high stroke rates and at metabolic powers which emphasize anaerobic metabolism (4). A limited evaluation of high-velocity (intensity) training has been shown to improve biomechanics and metabolism in competitive events (16).

The purpose of this study was to determine the effects of a novel training regime using higher-velocities and shorter training distances, on the stroke frequency-velocity relationship, energy cost of swimming, and metabolic power and capacity. Further, the outcome of this high-velocity training, i.e., the improvement in competitive swim performance, will be compared to results previously reported for standard conventional swim training.

Methods

Subjects: The subjects for this study were Division I University male swimmers. The high-velocity group (comprised of two groups of freshman recruits) were tested every September, December and March during their four-year careers. Twenty-two men who were 19.0 ± 0.2 years of age, 181 ± 1.3 cm in height, 75.02 ± 3.2 Kg in body weight, and 8.1 ± 2.1% body fat, participated.

The pre-college training of the swimmers ranged from 60,000 to 80,000 yards per week. In most cases, pre-college training involved both dry-land exercise and weight training. The results of the freestyle swimmers whose primary events were the 100-yard and 200-yard swims are presented. There were too few subjects for analysis of other strokes and distances. The initial performance times for the 100-yard and 200-yard freestyle were 48.66 ± 0.70 sec and 1:50.17 ± 2.72 sec respectively.

Biomechanical Parameters: The stroke frequency-velocity relationship, as shown by Craig, was determined for each swimmer. The subjects completed a series of swims where they pushed off the sidewall of the pool and swam one width of the pool (22 meters) at a constant stroke rate and velocity. The swimmer started at his minimal stroke rate and tried to achieve the greatest distance of body travel per stroke. With each subsequent swim, the stroke rate was increased while trying to maintain the maximal distance per stroke, until the swimmer felt he had achieved his maximal speed. Thereafter, the subject was encouraged to increase his stroke rate and not concentrate on his distance per stroke. Repeat swims with higher stroke rates were completed until there was no further increase in velocity with increased stroke rate, thus defining maximal velocity. The time and distance (about 10 meters) to swim a predetermined number of strokes was measured during each swim. From these data, the stroke rate, distance per stroke and mean velocity were calculated (10,11). In the first month of the first year, each swimmer was tested on several occasions to insure that the maximal velocity was determined for all stroke rates. The maximal value of velocity for each stroke rate was used to plot the curve used for training. The "swim meter," described by Craig (10,11), was also used in most swims to determine changes in instantaneous velocity during each swim. The data for changes in instantaneous velocity observed during testing were used by the coach to fine tune the swimmer's technique specifically by emphasizing the parts of the stroke that caused acceleration and eliminating aspects of the stroke that resulted in deceleration.

Metabolic Parameters: Two series of metabolic experiments were conducted on each swimmer. The first series was conducted in an annular (donut-shaped) pool, 58.6m in circumference and 2.5m wide and deep. The swimmer followed a monitoring platform that was driven at a pace set by a water flowmeter (water speed). The swims started at 0.9 m/sec for three minutes and then, the velocity was increased 0.1 m/sec every two minutes until the swimmers could no longer maintain the speed. Each swim lasted between 8 and 16 min. The subject wore a nose clip and mouthpiece. Expired ventilation was collected in Douglas bags on the monitoring platform during the second minute of each velocity. The volume of the gas was measured with a dry gas meter; the fractions of oxygen and carbon dioxide were determined by a medical gas analyzer (Perkin-Elmer 1100). Oxygen consumption and carbon dioxide production were calculated by standard equations. All equipment was calibrated prior to each experiment. These data represented the energy cost of swimming for aerobic speeds. The (VO_2) vs. velocity relationship was plotted, and the max VO_2 (plateau of VO_2-velocity) and energy cost of swimming (VO_2/velocity) were determined.

To determine the energy cost of swimming at high speeds, and the anaerobic power and capacity, the experiments were conducted in the competition pool, configured for 25-yard swims. The anaerobic power requirement is the difference between the rate of total energy requirement and that supplied by oxidative metabolism. When the rate of the energy cost of swimming is higher than the aerobic maximal, the swimmer will stop or slow down. To determine these parameters, the swimmers were divided into heats of four by their competitive times, in order to foster competition. Swimmers completed a 100-yard swim, waited one hour and then, swam a 200-yard distance. On a separate day, two days later, the swimmers swam a 50-yard competition, waited an hour and then, swam a 400-yard distance. Immediately after each swim the swimmers reported to a heated measurement station and were covered with robes. At 7, 8, and 9 min after the swim, blood samples were drawn from an anti cubital vein. The blood samples were spun in a centrifuge and lactic acid was determined by enzymatic techniques. Based on a previous study, the energetic contribution of high-energy phosphates was considered negligible (4), and the rate of lactate accumulation in the blood was calculated from the swim time and lactate concentration. Assuming this value was the peak lactic acid in the blood and that there was uniform dilution of lactic acid in the fast-water compartments of the body, the rate of accumulation of lactate was converted to an oxygen equivalent (3 ml O2/mM/kg), based on the swimming data of di Prampero (4,12). The oxygen equivalent of the lactate data for the high velocity swims were added to the VO_2 max and plotted with the VO_2-velocity data that was determined during the aerobic swims. This calculation represented the rate of energy cost of swimming (E_T) across all velocities, including competitive velocities. The maximal anaerobic capacity was assumed to be the highest value of peak lactic acid concentration after the 50, 100, 200 and 400-yard swims.

Swimming Performance: Performance data were evaluated based on times recorded from an invitational meet in December of each year, and in the Conference meet at the end of each of the four seasons. The times from the electronic timers used in the meets represented the performance data for all competitive distances.

Training paradigms: The high-velocity program used in this study was based on the biomechanical and metabolic data collected in the pre- and mid-season of each year, for each individual swimmer. The training program lasted 26 weeks during the competitive collegiate swimming and academic year. Although most swimmers trained in the summer, there was no specific training schedule given to them. The swimmers in the high-velocity group did not do dry-land training (27) or strength training (16,25). The high-velocity training was based on the stroke frequency-velocity relationship, which was determined at the beginning and mid-season of each of the four years, and a 10% increase each year of the velocities for all stroke frequencies was calculated ("shifting the curve"). During all four phases of training in the high-velocity group, each swimmer was required to swim at a specific velocity, at a given stroke frequency, that was his maximal distance per stroke for each stroke rate, i.e., swim "on the curve." During all training sessions of the high-velocity group, the coach spot checked each swimmer's swimming velocity and stroke rate using a stroke watch (Neilsen-Kellerman). He then gave verbal feedback during the rest intervals. Each training session was preceded by a warm-up of 20-30min. During the warm-up the velocity was progressively increased from an average of 1.3 m/sec to the training velocity to be used in that training phase. A 20-30min cool-down, where velocity was decreased progressively, followed each session.

The general principal of high-velocity training was to shift each swimmer's observed curve to a new theoretical curve and teach the swimmer to achieve the distance per stroke necessary to achieve the desired new velocity ("dialed in"). This shift was accomplished by first improving the swimmer's biomechanics through verbal feedback based on the observed velocity and stroke frequency. Initially (Phase I or Biomechanical Phase), this was achieved at low speeds where the swimmer could concentrate on trying new biomechanical patterns of stroking (without metabolic stress). When the swimmer could achieve the desired velocity with the desired stroke rate for two successive sessions, the stroke rate and velocity were increased, while the swimmer maintained the distance per stroke ("swimming on the curve"). This training phase also served to stress the musculature, as it required high force generation to maximize the distance per stroke. This phase of the training lasted approximately 2-3 weeks. The average velocities during this phase were 1.32 m/sec initially and were increased to 1.56 m/sec over 2-3 weeks.

The swimmer then moved to Phase II when it was demonstrated that he could swim at the desired velocities using set stroke frequencies. If a swimmer could not achieve the shift in two weeks, his new curve was adjusted to the maximal distance per stroke that he achieved in Phase I. In general, learning of the biomechanical patterns involved more rolling and stretching with the stroke, by emphasizing the entry and early pull, and minimizing the late push past the shoulder. The swimmer was encouraged to "get on top of the water" and minimize his leg kick.

The second phase of the training program (Phase II, aerobic metabolic phase) was started when the swimmer could swim on his curve up to his aerobic maximal. Phase II of the training was designed to improve maximal aerobic power and lactic acid clearance. The training involved swimming on the curve at speeds that the swimmer could only sustain continuously for 10 minutes (115-129% of VO_2 max). During the next 10 minutes, the swimmer swam continuously at 60% of his VO_2 max to optimize lactic acid clearance. This cycle was repeated three times over a one-hour training period. During the 6 to 7 weeks of this cycle, as the subject's metabolic power increased, the average velocity was increased from 1.61 m/sec to 1.81 m/sec.

Phase III (anaerobic metabolic phase) was designed to increase stroke frequency to the maximal velocity, maintain or improve VO_2 max, and add training of the anaerobic metabolic systems. During this 15-16 week phase, the swimmers swam at progressively higher stroke frequencies and velocities, while swimming on their curves. The stroke frequency was increased when the swimmer could achieve an entire session at the prescribed stroke frequencies and velocity, for two sessions in a row. At the beginning of this phase, a series of 16 repeated 25-yard swims with 15sec rest, followed by 1.5min rest, were continued over a one-hour practice session. After the swimmers were able to swim the entire hour on their curve for two sessions in a row, the rest intervals were shortened to 10sec. After one hour of 25-yard swims on the curve was achieved, the swimming distance was increased to 50 yards with a rest interval of 30sec, for a series of 16 repeated swims. As the swimmer improved, the rest interval was progressively decreased to 20sec. Although the swimming distances were short, the rest intervals were short as well. Thus, the aerobic and anaerobic systems were employed over the one-hour practice. Due to the progressive increase in both stroke rate and velocity during the training, the swimmers did not fatigue. However, if a swimmer could not maintain both the stroke rate and velocity during a given session, their stroke rate and velocity were reduced to the preceding level until they recovered. The swimmers progressed to the highest stroke frequencies and velocities that they could achieve during Phase III. This was the stroke rate and velocity that they swam during competition.

A fourth phase of the program was incorporated 21 days prior to their final meets. This phase included ½ hour of 25-yard interval swims with 10sec rest, at progressively increasing stroke rates and velocities. No taper (in the conventional sense) was included in this program. The swimmers trained up to three days prior to conference and national meets.

The training in all four phases was conducted in cycles of two high-velocity days that were followed by two recovery days. The high-velocity days followed the schedule described above. The two recovery days involved short (less than 15 sec) swims with 2-3 minute rest periods. It was assumed that this strategy used primarily high-energy phosphates and did not stress glycogen stores (4). Also included, were low velocity short distance warm-up swims. The recovery days were used to emphasize swimming technique (biomechanics) as well as techniques for starts and turns, by using the swim meter. The two high-velocity days maximized stress and the two recovery days allowed complete recovery, thereby, allowing the swimmers to do quality workouts each high-velocity day without incurring chronic fatigue. The two high-velocity and two recovery day schedule was designed to reduce muscle glycogen during training days and to insure complete recovery of glycogen stores during the rest days (6,7).

Statistical Analysis: Mean and standard deviation data were calculated for all variables. The data from the two groups of swimmers in the high-velocity group were combined for analysis. The data from the high-velocity group were compared as a function of year for each measured parameter by Analysis of Variance for Repeated Measures (ANOVA-RM). To simplify the graphs, only the mean data are shown for the high-velocity group. The variation between swimmers did not influence the ANOVRP as each subject served as their own control.

Results

Subjects: All of the swimmers came from high school or club programs that were using long-distance training programs. As such, the swimmers had to become accustomed to the shortness and intensity of the new program. By the second year the swimmers were, entrenched in, and enjoyed the program. The stroke frequency, velocity, distance, rest intervals and intensity of swimming changed progressively in the high-velocity group and eliminated boredom with the training. There were no significant changes in height, body weight, or body fat over their four years of participation.

Biomechanical Parameters: The stroke frequency-velocity data collected at the end of each season during the four years of training, are shown in Figure 1. Judged qualitatively, training did not affect the shape of the stroke frequency-velocity relationship. The velocities at all stroke frequencies increased significantly from the first to the fourth year, representing a 26% increase. This increase was due to increases in the maximal distance per stroke (16%) and maximal stroke frequency (8%). The range of coefficients of variation of velocity over the range of stroke frequencies tested was 12% to 21%. The shifts in the stroke frequency-velocity relationship within a specific year were about 50% from pre- to mid-season and 50% from mid- to end-season.

Metabolic Parameters: The data for aerobic and anaerobic metabolism at the end-season for the four years of training are shown in Figure 2. These data show that the energy cost of swimming (VO_2/velocity, expressed as oxygen equivalents) decreased significantly over the range of aerobic and competitive velocities. Judged qualitatively, the shape of the curves was similar. The changes in the rate of energy cost were 30% at 1.2 m/sec and 56% at 1.6 m/sec; the latter being the highest velocity observed in year 1.

The maximal speed that could be sustained aerobically (31%) and the maximal speed (27%) increased over the four years (Fig. 2). The maximal aerobic power increased from 3.28 ± 0.12 to 3.93 ± 0.21 to 4.32 ± 0.542 to 4.64 ± 0.57 to

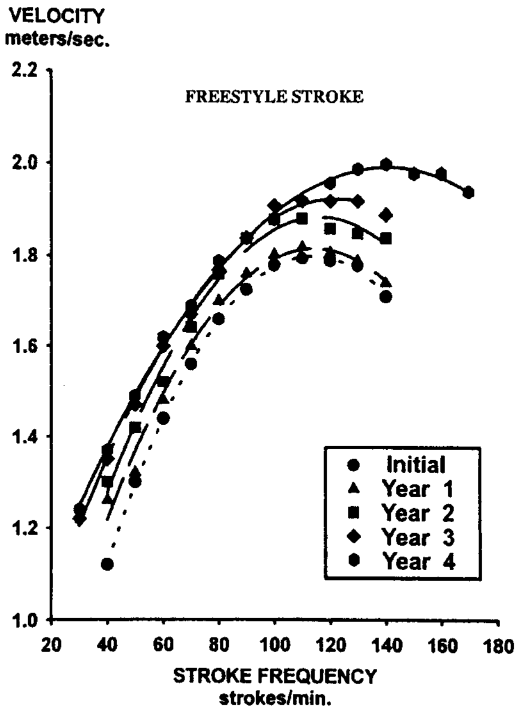

Figure 1. The stroke rate-velocity curve is plotted for the pre-test in year one (initial) and the end-season test for years 1, 2, 3, and 4. Velocity is plotted as a function of stroke frequency. The data are average values for all freestyle swimmers. The data for years 2, 3, and 4 were significantly greater than for year 1 (ANOVA-RM, $p < 0.05$).

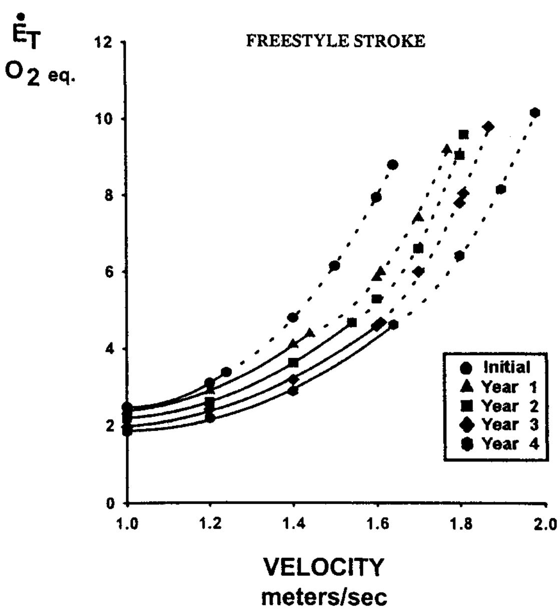

Figure 2. The energy cost of swimming, expressed as oxygen equivalents (E_T), is plotted as a function of swimming velocity. The data are mean values for the pre-test in year 1 (initial) and end-season tests for years 1, 2, 3, and 4. The solid lines are values measured directly, with the final point representing VO_2 max. The dashed line was estimated from values of lactic acid (12). The values for energy cost at all speeds were significantly less for end-season tests at years 1, 2, 3, and 4 than initial test (ANOVA-RM, $p < 0.05$). The values for VO_2 max, maximal velocity and maximal energy output were significantly greater for the end-season tests at years 1, 2, 3, and 4 than initially (ANOVA-RM. $p < 0.05$).

4.86 ± 0.63 l/min over the four years of training (Fig. 2, page 13). These increases represent a 20%, 9%, 8% and 5% increase in $\dot{V}O_2$ max for years 1 through 4, respectively, or a 48% total increase.

The maximal post-swim peak lactic acid concentrations were 8.71 ± 0.59, 11.06 ± 0.83, 11.29 ± 0.71, 11.97 ± 1.29, and 11.59 ± 0.88 mM for year 1 (initial), end-season years 1,2,3 and 4, respectively. There was a significant increase in peak lactic acid in the first year (27%). However, the value did not change significantly in years 2, 3 or 4. These peak lactic acids represent anaerobic capacities 1.93, 2.48, 2.54, 2.69, and 2.61 l O_2 equivalents, resulting in a 35% total increase in anaerobic capacity over the four years of training. The maximal total (aerobic + anaerobic) power increased from 8.95 to 9.36 to 9.77 to 10.0 to 10.36 l/min O_2 equivalents over the four years of training. This represented a 16% increase in total power while swimming.

Swimming Performance: The 100 and 200-yard events include both the sprint and middle distance swimmers on the team. The percentage improvements for the 100-yard event were 2, 4, 2, and 2% in years 1-4 respectively, or 10% total. The percentage improvements for the 200-yard event were 1.9, 3.1, 2, and 1.3% in years 1-4 respectively, or 8.3% total. These 8-10% improvements can be compared to a 1-3% or less improvement in 100- and 200- yard events previously reported for Division I collegiate swimmers training with traditional long-distance programs (9).

During the competitive events, the coach of the high-velocity group measured each swimmer's stroke rate and velocity to make sure that the swimmers were swimming on their curves, thereby, insuring optimal performance.

Improvements in swimming performances for distances other than the 100-yard and 200-yard freestyle, or for other strokes where only 2 to 4 swimmers competed, had improvements similar to the 100-yard and 200-yard freestyle for both the high-velocity and long-distance groups. Over the four years, improvements in the 50 yard, 500 yard and 1650 yard freestyle events were 4.59%, 4.42% and 4.89% respectively. Improvements over the four years in the backstroke, breaststroke and butterfly averaged for all distances, were 5.8%, 4.6% and 6.3% respectively.

Discussion

The present study demonstrated that Division I collegiate level swimmers using the high-velocity program described in this study, improved their stroke mechanics and metabolism sufficiently to improve performance by 8% to 10%, for the 100- and 200-yard freestyle, respectively. The improved performance due to the high-velocity training was greater than the 1-3% improvements observed for the more conventional long-distance programs.

The unique aspects of this program are that the swimmers train using the stroke frequency-velocity curve. First, they train at slow speeds to improve distance per stroke. Second, they train at the highest velocity that the maximal distance per stroke can be maintained (maximal aerobic power, anaerobic capacity, stroke mechanics and muscular strength). Third, they train at progressively higher velocities and stroke rates up to maximal (maintenance of aerobic power, stroke rates, anaerobic power, maximal stroke frequencies and velocity). The swimmers described here did not participate in strength training. For the past 30 years, it has been recommended that over-distance training be used to increase the swimmer's aerobic base (11). However, nearly ten years ago, it was suggested that training should emphasize improving biomechanics (11). This type of training involves training with slow stroke frequencies, thus achieving a longer distance per stroke, and then, swimming at progressively faster velocities, and thus short intervals (swimming on the curve) (10,11). It has previously been suggested that optimal swim training should improve biomechanical as well as metabolic weaknesses (28). While swimmers comply with prescribed training distances, rest intervals and even stroke frequencies, they are not able to judge velocity or intensity of swimming very well (26).

Physical characteristics: The swimmers in this study were of similar body size and composition as reported by other studies and these parameters did not change significantly during the four years of training. Thus, improvements observed here are not thought to be due to changes due to growth or maturity.

Biomechanical Parameters: It has previously been reported that elite swimmers have stroke frequency-velocity curves that are shifted up and to the right, greater distances per stroke, and higher stroke rates and velocities compared to less competitive swimmers (5,10,11). The stroke frequency-velocity relationship, when shifted up and to the right, has been shown to be associated with a reduced energy cost of swimming (30). High performance is related to higher stroke rates, greater distance per stroke and the ability to sustain these throughout the race (5,10,11). For most elite swimmers, the shape of the stroke frequency-velocity curves for a specific stroke are similar (10,11). Thereby, improving performance would necessitate a shift in the curve up and to the right. The data from the present study demonstrate that it is possible to shift the stroke frequency-velocity curve by as much as 10% per year, or 40% over four years. Although the data could not be analyzed statistically due to the small number of swimmers, similar improvements were observed in the other competitive strokes and distances. A significant shift in the stroke frequency-velocity curve for competitive velocities would not be expected in swimmers trained with long-distance. This later hypothesis needs to be tested on a population of swimmers engaged in a contemporary over-distance-based program.

Metabolic Parameters: Maximal aerobic power: The present program used three 10min swims at 115-125% of maximal aerobic power. During these swims, lactic acid built up at a rate of 1 to 1.5 mM/min, resulting in maximal lactates being reached after 10min. Ten minutes of slow swimming (60% VO_2 max) was allowed between bouts. This has been shown to be sufficient to clear lactate from the blood (1,12,31). Maximal aerobic power during swimming in low-level swimmers is quite low (3.0-3.5 l/min) (4,8,12,19). The first year VO_2 max values (3.5-4.0 l/min) in this study and other studies (4,16) on higher-level swimmers were similar to values previously reported for less competitive swimmers (12,19). Over-distance training has been reported to result in 4-11% improvement in VO_2 max in one season (19,22,31). However, in the present study, VO_2 max improved 20% in the first year and 40% overall. Other studies have shown that increasing training distance from 4,266 to 8,970 m/day did not significantly affect performance or metabolic power (13,17), and that over-distance training for 5 months does not significantly increase VO_2 max (23). Increasing training distance for 10 days (8,970 m/day) did not increase performance, aerobic capacity, or muscle citrate synthase; however, muscle glycogen was lower than when training 4,266 m/day (6). It may be that low intensity swimming does not provide a sufficient stimulus, or rather, the appropriate stimulus, to improve VO_2 max and that higher exercise intensities, as used in this program and that of a previous study (16), are needed to improve VO_2 max. These data are supported by a study demonstrating that improvements in performance are significantly correlated with mean swimming velocity (intensity), but not training distance or frequency (22).

Swimming performance has been related to the peak lactic acid in blood (1). The data from the present study indicate that the rate of the anaerobic contribution (power) to swimming performance was increased 16% by high-velocity training over the four years of training. The maximal peak lactate increased 35% over the 4 years of training. Previous studies have shown that 8 weeks of high-velocity training increased lactate by 20% over moderate intensity training (15).

High-velocity interval swimming with rest intervals of 30sec resulted in lower lactate levels than swims with 10sec rest intervals for distances of 50 to 100 m. The high velocity training in the present study used 25-yard swims, starting with 30sec rest and decreasing to 10sec rests, thereby, maximizing swimming velocity and oxygen consumption while delaying the limitation imposed by muscle or blood acidosis. Furthermore, the magnitude of the increase in anaerobic power was greater than the increase in anaerobic capacity (as assessed by lactic acid concentration), suggesting that there was increased buffering of lactate by the tissues. Presumably, this happens through increased lactate uptake by the slow twitch fibers within the muscle while fast twitch fibers are producing it.

Summary

The present study examined the competitive swim performance of swimmers trained on a high-velocity and short-distance program without strength training or a traditional taper. A major factor in the swimmers' training was the ability to use the stroke-frequency and velocity relationship to progressively increase the velocity (intensity) of swim training.

The performance improvements from the stroke-based and high-velocity training program are supported by the improvements in the stroke frequency-velocity and total energy-velocity data. The distance per stroke at all stroke frequencies was increased, which led to a decreased energy cost of swimming at all velocities. In addition, there were significant increases in maximal aerobic power, and anaerobic power and capacity, leading to the ability to achieve and maintain higher velocities. Although it was impossible to assess biomechanical and metabolic changes of swimmers complying with a traditional over-distance-based program, a previous study using similar training programs (long-distance) on similar swimmers resulted in improvements that were at least 50% less than the improvements reported here for the stroke-based high-velocity training (9).

It is reasonable to speculate that lower intensity programs do not provide sufficient stress or the appropriate stimulus to cause optimal adaptations. This type of conventional training likely leads to decreased glycogen stores and chronic fatigue. Together, this would compromise training and competitive swim performance. This is supported by the observations that long-distance training decreases sprint swim performance, or prevents specific improvements, during the training season. Long-distance training requires a taper for recovery of performance, but the improvements are still significantly less than those reported resultant from the stroke-based, high-velocity (intensity) program used in this study. The program used in this study has built-in rest intervals within and between days of training with the most intense exercise limited to one hour per day.

The evidence presented here suggests that high-velocity training programs can be successful. Furthermore, programs which heavily rely upon dry-land strength training and long-over-distance sets should be reevaluated. Because we have no evidence to suggest otherwise, it is likely that this novel, unconventional training may be equally suited to elite swimmers as well as the more average athlete.

References

1. Avlonitou E.. Maximal lactate values following competitive performance varying according to age, sex,

and swimming style. J. Sports Med. Phys. Fit. 36(1):24-30, 1996.

2. Bonifazi M., G. Martelli, L. Marugo, F. Sardella and G. Carli. Blood lactate accumulation in top level swimmers following competition. J. Sports Med. Phys. Fit. 33(1):13-18, 1993.
3. Capelli C., P. Zamparo, A. Gigalotto, M.P. Francescato, R.G. Soule, B. Termin, D.R.Pendergast and P.E. di Prampero. Bioenergetics and biomechanics of front crawl swimming. J. Appl. Physiol. 78(2):674-679, 1995.
4. Capelli C., D.R. Pendergast and B. Termin. Energetics of swimming at maximal speeds in humans. Europ. J. Appl. Physiol. Occ. Physiol. 78(5):385-393, 1998.
5. Chollet D., P. Pelayo, C. Delaplace, C. Tourny, and M. Sidney. Stroking characteristic variations in the 100-M freestyle for male swimmers of differing skill. Perceptual Motor Skills 85(1):167-177, 1997.
6. Costill D.L., M.G. Flynn, J.P. Kirwan, J.A. Houmard, J.B. Mitchell, R. Thomas R, and Park S.H.. Effects of repeated days of intensified training on muscle glycogen and swimming performance. Med. Sci. Sports Exerc. 20(3):249-254, 1988.
7. Costill D.L., W.J. Fink, M. Hargreaves, D.S. King, R. Thomas and R. Fielding. Metabolic characteristics of skeletal muscle during detraining from competitive swimming. Med. Sci. Sports Exerc. 17(3):339-343, 1985.
8. Costill D.L.., J. Kovaleski, D. Porter, J.P. Kirwan, R. Fielding and D. King. Energy expenditure during front crawl swimming: predicted success in middle distance events. Intl. J. Sports Med. 6:266-270, 1985.
9. Costill D.L.. Less may be best. Swim Magazine. September/October 25-31,1992.
10. Craig AB, Jr. and D.R. Pendergast. Relationship of stroke rate, distance per stroke, and velocity in competitive swimming. Med. Sci. Sports Exerc. 11(3):278-283, 1979.
11. Craig A.B., Jr., P. Skehan, J.A. Pawelczyk and W.L. Boomer. Velocity, stroke rate, and distance per stroke during elite swimming competition. Med. Sci. Sports Exerc. 17(6):625-634, 1985.
12. Di Prampero, P.E., D.R. Pendergast, D.W. Wilson and D.W. Rennie. Blood lactic acid concentrations in high velocity swimming. Swimming Medicine IV, eds. B. Eriksson and B. Furberg, Univ. Park Press, 249-261, 1978.
13. Fitts R.H., D.L. Costill and P.R. Gardetto. Effect of swim exercise training on human muscle fiber function. J. Appl. Physiol. 66:465-475, 1989.
14. Hooper S.L., L.T. Mackinnon and A. Howard. Physiological and psychometric variables for monitoring recovery during tapering for major competition. Med. Sci. Sports Exerc. 31(8):1205-1210, 1999.
15. Houston M.E., D.M. Wilson, H.J. Green, J.A. Thomas and D.A. Ranney. Physiological and muscle enzyme adaptations to two different intensities of swim training. Europ. J. Appl. Physiol. Occ. Physiol. 46(3):283-291, 1981.
16. Kame V.D., D.P. Pendergast and B. Termin. Physiological responses to high intensity training in competitive university swimmers. J. Swim. Res. 6(4):5-8, 1990.
17. Kirwan J.P., D.L. Costill, M.G. Flynn. J.B. Mitchell, W.J. Fink, P.D. Neufer, J.A. Houmard. Physiological responses to successive days of intensified training in competitive swimmers. Med. Sci. Sports Exerc. 20(3):255-259, 1988.
18. MacKinnon L.T., S.L. Hooper, S. Jones, R.D. Gordon and A.W. Bachmann. Hormonal, Biomechanical and metabolic swim training, immunological, and hematological responses to intensified training in elite swimmers. Med. Sci. Sports Exerc. 29(12):1637-1645,1997.
19. Magel J.R., G.F. Foglia, W.D. McArdle, B. Gutin, G.S. Pechar and F. Katch. Specificity of swim training on maximal oxygen consumption. J. Appl. Physiol. 38:151-155, 1975.
20. Mujika I., S. Padilla, A. Geyssant and J.C. Chatard. Hematological responses to training and taper in competitive swimmers: relationships with performance. Arch.Physiol. Biochem. 105(4):379-385, 1998.
21. Mujika I., T. Busso, L. Lacoste, F. Barale, A. Geyssant and J.C. Chatard. Modeled responses to training taper in competitive swimming. Med. Sci. Sports Exerc. 28(2):251-258, 1996.
22. Mujika I., J.C. Chatard, T. Busso, A. Geyssant, F. Barale F and L. Lacoste. Effects of training on performance in competitive swimming. Can. J. Appl. Physiol. 20(4):395-406, 1995.
23. Neufer P.D., D.L. Costill, R.A. Fielding, M.G. Flynn and J.P. Kirwan. Effect of reduced training on muscular strength and endurance in competitive swimmers. Med. Sci. Sports Exerc. 19:486-490, 1987.
24. Reilly M.F., V.D. Kame, B. Termin, M.E. Tedesco and D.R. Pendergast. Relationship between freestyle swimming speed and stroke mechanics to isokinetic muscle function. J. Swim. Res. 6(3):16-21, 1990.
25. Roberts A.J., B. Termin, M.F. Reilly and D.R. Pendergast. Effectiveness of biokinetic training on swimming performance in collegiate swimmers. J. Swim. Res. 7(3): 5-11, 1991.
26. Stewart A.M. and W.G. Hopkins. Swimmers' compliance with training prescription. Med. Sci. Sports Exerc. 29(10):1389-1392, 1997.
27. Tanaka H., D.L. Costill, R. Thomas, W.J. Fink and J.J. Widrick. Dry-land resistance training for competitive

swimming. Med. Sci. Sports Exerc. 25(8):952-959, 1993.

28. Toussaint H.M., and A.P. Hollander. Energetics of competitive swimming. Implications for training programs. Sports Med. 18(6):384-405, 1994.
29. Trappe T., A. Gastaldelli, A.C. Jozsi, J.P. Troup and R.R. Wolfe. Energy expenditure of swimmers during high volume training. Med. Sci. Sports Exerc. 29(7): 950-954, 1997.
30. Wakayoshi K., L.J. D'Acquisto, J.M. Cappaert and J.P. Troup. Relationship between oxygen consumption, stroke rate, and swimming velocity in competitive swimming. Int. J. Sports Med. 16(1):19-23,.1995.
31. Wakayoshi K., T. Yoshida, Y. Ikuta, Y. Mutoh and M. Miyashita. Adaptations to six months aerobic swim training. Changes in velocity, stroke rate, stroke length and blood lactate. Int. J. Sports Med. 14(7):368-72, 1993.