STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH

31

Kari Lasse Keskinen

Stroking Characteristics of Front Crawl Swimming

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 1993

STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH 31

Kari Lasse Keskinen

Stroking Characteristics of Front Crawl Swimming

Esitetään Jyväskylän yliopiston liikuntatieteellisen tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston Liikunnan salissa (L304)
joulukuun 18. päivänä 1993 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Sport and Health Sciences of the University of Jyväskylä,
in Auditorium L303, on December 18, 1993 at 12 o'clock noon.

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 1993

Stroking Characteristics of Front Crawl Swimming

STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH 31

Kari Lasse Keskinen

Stroking Characteristics of Front Crawl Swimming

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 1993

URN:ISBN:978-951-39-7911-9
ISBN 978-951-39-7911-9 (PDF)
ISSN 0356-1070

ISBN 951-34-0143-X
ISSN 0356-1070

Jyväskylän yliopistopaino
and SisäSuomi Oy, Jyväskylä 1993

ABSTRACT

Keskinen, Kari Lasse
Stroking Characteristics of Front Crawl Swimming
Jyväskylä: University of Jyväskylä, 1993, - 77 p
(Studies in Sport, Physical Education and Health
ISSN 0356-1070; 31)
ISBN 951-34-0143-X
Diss.

The aim of the study was to find explanations for the great variability of the technique performances of swimmers, observed during competition and practice. The study also aimed to find practical methods of data presentation in order to be able to follow the technique development of swimmers during the training process. Special interest was focused on investigating the effects of enhanced swimming intensity on the stroking strategy and the interrelationships between the stroke parameters during exercise. Mean velocity (v), stroke rate (SR), stroke length (SL), and stroke index (SI), as well as the duration of different phases of a stroke cycle, were considered as the parameters to describe the stroking characteristics of front crawl swimming. Blood lactate concentration (BLa) in relation to v was used to define the intensity categories during the tests. The subjects were 87 well-conditioned male competitive swimmers representing five different samples taken to participate in the studies. The results showed that the initial stroking strategy in training conditions was not very much different from that observed in competitions, reported in the scientific literature. Several factors, however, were noticed to effect the stroking strategy. The absolute values of v, SR, SL and SI changed with the enhancement in swimming intensity, and the five intensity categories were characterised by different relationships among the stroke parameters. The results also demonstrated that the physiological responses of the swimmers during exercise could be attributed to the variables of technique performance. The major findings showed that the changes in the SL could be connected with parallel changes in blood lactate concentration, especially around the aerobic-anaerobic transition. Thus, it is suggested that the measurement of technique variables, under the influence of physiological stress and simultaneously with the physiological parameters, by examining the relationships between v, SR and SL in standardised pool testing conditions, should be a part of the control of training in swimmers.

Key words: front crawl swimming, stroking characteristics, blood lactate concentration, aerobic/anaerobic loading

CONTENTS

PREFACE

This thesis is based upon the results of the following original papers. They will be referred to in the text by their Roman numerals.

(I) Keskinen, K.L. & Komi, P.V. (1988) Interaction between Aerobic/Anaerobic Loading and Biomechanical Performance in Free Style Swimming. In: Swimming Science V (editors B.E. Ungerechts, K. Wilke and K. Reischle), International Series on Sport Sciences, 18: 285-293. Human Kinetics, Champaign, Illinois.

(II) Keskinen, K.L. and Komi, P.V. (1988) The Stroking Characteristics in Four Different Exercises in Free Style Swimming. In: Biomechanics XI-B (editors G. de Groot, A.P. Hollander, P.A. Huijing and G.J. van Ingen Schenau), p. 839-843, Free University Press, Amsterdam, The Netherlands.

(III) Keskinen, K.L. and Komi, P.V. (1989) Interaction between Swimming Technique and Performance Capacity in Swimming. In: Congress proceedings of XII Congress of Biomechanics (editors R.J. Gregor, R.F. Zernicke and W.C. Whiting), abstract nb 83. University of California, Los Angeles.

(IV) Keskinen, K.L., Tilli, L.J. and Komi, P.V. (1989) Maximum Velocity Swimming: Interrelationships of Stroking Characteristics, Force Production and Anthropometric Variables. Scandinavian Journal of Sports Sciences, 11(2): 87-92.

(V) Keskinen, K.L. and Komi, P.V. (1992) Effect of Leg Action on Stroke Performance in Swimming. In: Biomechanics and Medicine in Swimming; Swimming Science VI (editors D. MacLaren, T. Reilly and A. Lees), p. 251-256. E & FN SPON, London.

(VI) Keskinen, K.L. and Komi, P.V. (1993) Stroking Characteristics of Front Crawl Swimming during Exercise. Journal of Applied Biomechanics, 9(3): 219-226.

The studies have been performed in the Department of Biology of Physical Activity at the University of Jyväskylä. The Foundation for Promotion of Physical Culture and Health provided the swimming facilities to carry out the experiments. The studies have been supported financially by grants from the Finnish Central Sports Federation (1985-1986), the Ministry of Education (9275/78/87; 8576/78/88; 80/722/89; 172/722/90) and the University of Jyväskylä (1987, 1992). The travelling costs to international congresses have in part been paid by the Finnish Swimming Association and the Ministry of Education.

The process of preparing a manuscript resulting in a Doctoral Thesis, has included numerous hours of concentrated efforts over a long period. Not only myself as the author but also several other persons have helped me finish this project. I would like to extend warmest thanks to professor Paavo V. Komi, Ph.D, the head of the Department of

Biology of Physical Activity and the supervisor of this thesis, for his contribution and support during the process. He also has introduced me to an international network of scholars in my own area of interest.

I want to thank professor A. Peter Hollander, Ph.D. from the Vrije Universiteit Amsterdam and professor Mitsumasa Miyashita, Ph.D. from the University of Tokyo for their most valuable comments on the manuscript as the official examiners of the thesis.

I also want to thank Mr Lauri Tilli, B.Sc., Ms Ursula Salonen and Mr Hannu Hautamäki, B.Sc. for their contribution in data collection and analyses; Ms Taina Laakso, Mr Pasi Lohi, M.Sc. and Ms Raili Jokinen for preparing the figures; Mr Markku Tervakari and the technicians for their contribution in preparing the equipment; Dr Michael Coleman for checking the English language of the manuscript. I also want to thank Dr Keijo Häkkinen, Dr Antti Mero, Dr. Huub Toussaint, Mr Jarmo Perttunen, M.Sc., Mr. Reijo Pirttimäki, M.Sc., Mr. Kari Vuorinen, and Ms Hellevi Labbart for their collaboration in various matters.

Very special thanks goes to the subjects and their earlobes, which were willingly available for blood sampling during the experiments. Their sacrifices have been most valuable and I hope that the results will be utilised by the swimmers of today and tomorrow even more extensively than was done yesterday.

Finally, I would also like to express the very personal thanks to my wife Tarja and to our children Jukka-Pekka and Outi, who have been patiently waiting for this project to turn into an end at last. Without you, this work would have been ready in half the time, but, my life would not have been as enjoyable as it has been.

Kari Lasse Keskinen

1 INTRODUCTION

Swimming, like any other competitive sports event, sets general requirements which the sportsmen have to achieve during their performances. In swimming, the most significant requirements are set by the surrounding water itself. On one hand, it is the greatest hindrance for any kind of locomotion due to its great density. But on the other hand, the aquatic environment, although essentially strange and even hostile to humans, offers almost an unending selection of possibilities for various modes of techniques to be used by well-organised arm, leg, and trunk movements above and under the water surface. Therefore, one of the most important aspects which both the practitioners and scientists have to consider, is related to techniques and styles used by the swimmers during various situations of competition and practice.

Baumann (1992), a distinguished biomechanist, has said:

> "If effective application is of primary importance more pragmatic approaches have to be considered. This means that not only scientific methods and results and technical instruments can be used but also the empirical knowledge from practical coaching and training, from Physiology and Psychology, from Biomechanics and other sciences have to be exploited. In this way the empirical knowledge guides the research methodology and set-up. On the other hand, scientific theories and experimental findings influence the strategy and observation priorities in practice. The analysis of a movement technique and its physical conditions may give a clear description of the relations within a set of variables. This may be available for different levels of performance. However, this is not sufficient when an athlete has to be "transformed" from a given state into another one. If the adaptation processes, the biological reactions of the locomotor system to certain training measures are not known, it is possible to perform what is called "control of the training process". The study of these adaptive processes and the use of empirical knowledge is unavoidable."

Dillman (1989) specified:

> "If the Biomechanics field is to advance in the practical application of knowledge, new methods of data presentation will have to be developed."

Dillman's guide-line, however, is valid not only for Biomechanics but for other sciences as well. With these considerations in mind, this thesis aims to generate a theory from the practical biomechanical and physiological considerations of human locomotion in the aquatic environment, and to make further practical propositions. However, the primary aims and the designs used would merely be considered as a fundamental part of the Science of Sports Coaching, and especially of the Science of Swimming.

In general, it was the aim of the present study to try to find answers to questions which are related to some of the basic problems among swimmers and coaches:

- Why are the techniques of swimmers so variable during both competition and practice?
- Why are their technical performances continually changing during practice?
- Is it possible to measure technique performances in order to follow their development in swimming skills?

More specifically, the goal was to give answers to those questions by examining the effects of variable swimming conditions during training on mechanics and stroking performances, and by making comparisons with the known facts about competitive situations. Special interest was focused on investigating the effects of the enhancement of swimming intensity on stroke parameters and their interrelationships. A useful tool to merge all this information from various sources and of different levels of quantification could be the examination of stroking characteristics in practical training conditions.

1.1 Top performances while swimming

In order to examine top performances in aquatics, one has to refer to studies made in Zoology. In studies of animal locomotion in the water, most of the examples have been taken from fish swimming (see e.g. Alexander & Goldspink, 1977). It has been observed that fish swimming involves changes not only in the frequency but also in the amplitude of the tail beat, and as the speed of swimming increases there is an increase in both the frequency and the aptitude of the beat (Bainbridge, 1958). Furthermore, Bainbridge (1960, 1962) found that a 28-cm trout had top speeds around 2.8 $m*s^{-1}$ with a tail beat frequency of 18 Hz. A trained, 1.9 m long dolphin, more comparable to humans in size, was able to swim a 60-m course at 8.3 $m*s^{-1}$ (Lang & Norris, 1966). The power needed to propel this 1.9-m dolphin at 8.3 $m*s^{-1}$ speed was estimated to be about 1700 W (Alexander, 1975). Top speeds up to even 21 $m*s^{-1}$ have been estimated for some tunnies (Walters & Fierstine, 1964). All these values are far beyond the abilities of the humans at the same conditions. The most advanced human performances can be best described by referring to the swimming world records. The fastest competitive event, men's 50-m free style, has been covered at about 2.3 $m*s^{-1}$ speed.

1.2 Competitive swimming performances

Competitive swimming performances can be divided into three main elements: starting, turning and stroking (Miller, 1975; Hay, 1978). Their relative importance depends on the distance to be covered during a race. Hay (1987) presented data which was collected in freestyle events from 50 to 1000 yards in collegiate athletes swimming short course (25 yards) races. Time for starting occupied from less than half percent for the 1000 yards to 11 percent for the 50 yard event (in 25 y pools). The percentage of the total time spent turning ranged from 37 percent for the 1000 yard to 21 percent for the 50 yard event. Over one-third of the race time was spent turning in all events of 200 yards and longer. The percentage for the stroking time ranged from 63 for the 1000 yard to 69 percent for the 50 yard event. For the 100-m in long course, the time spent stroking may account up to about 80 percent. According to Thayer and Hay (1984) the time stroking accounted for 60-70 percent of the event time in the middle distances (200-400 yards).

1.3 Stroking characteristics of competitive swimming

While the time that a swimmer spends stroking occupies the major portion of the whole swimming race, it can be considered as the most significant part of the competitive performance in swimming. The average velocity (v) during stroking is the product of the average stroke length (SL) and the average stroke rate (SR). SL is equivalent to the distance the body is displaced during one complete stroke cycle. SR is the frequency of stroke cycles in a unit of time, either seconds or minutes (Hay, 1987).

East (1970) aimed to investigate the relationships between SR, SL and performance time in competitive 110-yard swimming. He found that faster times in the front crawl for men were characterised by increases in SR with slight decreases in SL. When male and female swimmers were compared across all strokes, they were found to have the same SR with differences in performance times being a function of their SL. The improvements in performance depended primarily upon the increase in SR in men's free style, increase in SL in men's backstroke and butterfly, and increase in both SR and SL in women's butterfly.

Hay & Guimares (1983) aimed to determine how the SL, SR and v varied during a course of 200-yard event in the four competitive strokes. The races of University of Iowa's men team (14 swimmers) were filmed throughout a training season and the analyses were reported for the 200-yd events. For each swimmer, the v was observed to decrease from lap one to lap eight throughout the race. The decline of the v was almost completely accounted for by decreasing SL while SR stayed essentially constant as the race progressed. The results suggested that the loss in v was primarily the result of a failure to maintain the SL at its initial level, probably due fatigue. Significant correlation between SL and v was found for freestyle, butterfly and breaststroke, but not between SR and v. A significant negative relationship was found between SL and SR for all four strokes.

Letzelter & Freitag (1982 and 1983) studied the free style swimming performances of top European swimmers (best 16) in the Championship finals (200-m event) and top German athletes (34 males and 34 females) in national Championships of BRD (100-m event). They aimed to examine: *On which laps do the stronger swimmers mainly secure their lead?, or Are all laps equally responsible for the advantage?*, and *Is it preferable to swim with longer strokes or with a higher SR?, or Are better swimmers superior in both variables?* It was observed that the velocity patterns for male and female swimmers were similar, although males were faster than females and elite swimmers were faster than the average competitive swimmers. In all cases, a significant reduction in v throughout the race was obtained. In 200-m swims the swimmers could slightly increase their speed in the final lap compared to the 2nd and 3rd laps. It was also observed that whereas women were obviously inferior in SL, they swam with practically identical SR. So SL was the only difference between male and female swimmers. The performance difference between the subgroups could not always be explained by a single variable. The faster males were superior in SL as well as in SR to the slower males. For women, SL was the only difference. The SL was found to decrease progressively for both male and female swimmers. The reduction of SL was the main reason for speed reduction after the starting lap. The increased v during the final lap was due to increased SR. The SR diagrams varied substantially and had different patterns on individual basis. The combination between SR and SL in producing v was individually arranged and the variation in both SL and SR was larger than their product v. The SR which was observed to counteract SL from lap to lap, increased from start until the end and reached the peak values on the final lap in men. Women followed a different pattern so that on the 2nd lap, SR decreased and then increased towards the end of the 200-m race.

The results of Pai & al. (1984) closely conformed to those of Letzelter & Freitag (1982, 1983) concerning the behaviour of the stroke parameters during the course of a race. They studied the finalists (male and female) in fifteen of the sixteen 100-m and 200-m individual swimming events in the 1982 British Commonwealth Games in Brisbane, Australia. They concluded that among elite swimmers, the combination of SL and SR in producing v may vary greatly and yet still produce very similar values for v. They suggested that this result may imply that no general optimum in SL versus SR relationship exists, and it therefore would seem to be an individual rather than a general optimum. They also reported that in all events, SR was significantly higher in 100 m events than in 200 m events; SL was longer in all 200 m events except the women's butterfly and men's backstroke.

Satori's observations from the major swimming championships from 1970's have demonstrated that the inter-individual differences in both competitive and stroking specific performances were significantly large (Satori, 1974, 1975, 1976, 1978, 1980). Swimmers of around the same performance level performed with highly different number of strokes, e.g. in 1500-m free style the amount of stroke cycles per 50-m lap varied between 26.5 and 18.5. The reason for this difference was most probably the effect of different leg action. This suggestion refers to the variants of the front crawl swimming. It is common knowledge that the six-beat and two-beat styles require a different kind of arm stroke frequencies. Similarly, also the men's 100-m race included correspondingly large differences between the individuals: Montgomery's 18.5+21 cycles and Bure's 28+32 cycles per lap (Satori, 1974). Other observations in major swimming competitions, e.g. in Soül Olympics 1988 (Nelson & al., 1990; Kennedy & al., 1990; Chengalur & Brown, 1992) and Pan Pacific Games 1989 (Wakayoshi & al., 1992,) reported closely similar findings to those of Satori's.

1.4 Stroking characteristics and adaptation to exercise

Craig & Pendergast (1979) examined the relationships between SR and speed. Repeated swims for a 22-m distance were made at speeds varying from slow to maximum. It was found that each swimmer increased his/her speed with the increase in SR. However, the maximum in speed was reached much earlier than was the case in SR. When SR was increased still further, the speed started to decrease, implying that there would be an optimum SR for each swimmer.

Craig & al. (1979) aimed to indicate how relationships of SR, SL and v can be useful in practice. The curves for SR versus v relationship were obtained on swimmers of varying skill. It was observed that those who had the longest SL at 20-25 strokes per min had the greatest maximal v. There was also a positive correlation between the degree of shortening and the maximal v. These two observations suggest that practice for competitive swimming should probably involve considerable swimming with slow SR (20-30 strokes per min) to achieve a greater SL. If a swimmer does not have a long SL in low speed swimming, there is less latitude for shortening and a greater dependence on SR to swim fast. The data of individual swimmers was presented before and after changing their stroke patterns. It was demonstrated that swimmers can increase their level of performance by increasing their SL. Thus, the v increases, SR maintains at the initial level or increases slightly at maximal level, and SL increases at any given v and SR.

Hay & Guimares (1983) aimed to determine the effects of regular training by examining how the SL, SR and v alter as performances improve over a season in the 200-yard events. This study yielded a significant correlation between v and SL over the course of a season in all competitive strokes except for the backstroke. No significant correlation was found between v and SR. It was suggested that the improvements in v over the course of a season were almost exclusively due to corresponding improvement of SL.

Craig & al. (1985) re-examined the same basic relationships and the absolute values of v, SR and SL in the 1984 USA Olympic Swimming Trials as was already done in 1976 (Craig & Pendergast, 1979). The mean v of nine out of ten women's events was greater in 1984 as compared to 1976. Three of the men's events showed improvement. In nine out of twelve events, the increased v was accounted for by increased SL (4-16 %) and in eight there was also a decrease in SR (3 - 13 %). The finalists in each event were compared to those whose v were 3-7 % slower. In almost all events and all strokes the finalists achieved greater SL than did the slower group. In the men's events, increased SL was associated with decreased SR.

Saito (1982) intended to reveal the relationships between v, SR and SL in the breaststroke and to determine whether the v is increased by an increased SR induced by breaststroke training. A group of 168 previously untrained male subjects (age 15-16 years, height 168±7.8 cm and weight 57±6.9 kg) took part in swimming lessons three times per week for a six week period. It was found that v and SL were increased significantly by the training. SR decreased slightly but this result was statistically non-significant. The correlation between v and SL were close both before and after the training but not between v and SR.

1.5 Stroking characteristics and anthropometric variables

Toussaint & al. (1983) investigated two groups of swimmers with different performance levels in order to examine the differences in anthropometric measures which could influence the flow of external power and the propelling efficiency while swimming. Elite swimmers differed from trained swimmers in arm length and in frontal area of the forearm and hand. The hand frontal area, especially when related to body length, was observed to be significantly different between the two groups. The SR did not differ between the groups but a significant difference was found in SL in favour of the elite group swimmers. It was concluded that the quality of anthropometric variables influence the propelling efficiency, but in order to increase the propelling ability the improvement of techniques should be an important objective in training for swimming.

Grimston & Hay (1986) determined the relationships between selected characteristics of the physiques of 14 male college swimmers and the SL and V they used during competitive free style events. Researchers found that the anthropometric variables accounted for 89 percent of the variance in SL, 41 percent of variance in SR and 17 percent in v. It was concluded that although v is little influenced by the physique of the swimmer, the combination of SL and SR used to attain that v appears to be very much a function of his physique.

Toussaint & al. (1991) studied the effects of artificial enlargement of the propelling surfaces of the hand in front crawl swimming. Researchers observed that the rate of energy expenditure, power output, and work per unit distance decreased significantly, whereas the propelling efficiency and work per stroke increased with paddle swimming. It was concluded that the increase in SL and the decrease in SR at a certain v, could be explained by the increase of the propulsive surface area.

Also Monteil & Rouard (1992) examined the influences of the size of the paddles in front crawl. The swimmers could increase the time spent in one stroke cycle with the increase in paddle size. No significant linear increase between the size of the paddles and electrical activity of the studied muscles was observed. The greatest muscular activity was obtained with medium sized paddles, commonly used for training, when compared with small and large sized paddles.

1.6 Stroking characteristics and possible effects of age

Rivera & al. (1986) collected data from the 100-m finals of the Puerto Rico's junior championships 1983. The study aimed to determine and evaluate v, SR and SL in competitive male and female infantile and juvenile elite swimmers representing age group categories for 9-10, 11-12, 13-14 and 15-17 years. Although the statistical analyses could not provide clear evidence, the data gives an idea of about the possible age-related changes that could occur within the relationships between v, SR and SL. The data shows that with the increase in age there was an increase in v and SL. On the other hand, in female groups and in all four strokes, the SR demonstrated slight but non-significant decrease when the age was increasing. In male swimmers the SR remained practically unchanged throughout the age categories in breaststroke and butterfly events, but increased slightly in backstroke and decreased slightly in front crawl. In order to be able to utilise these possible findings, the results should be reproduced with a more carefully selected sample of swimmers and research design.

Toussaint & al. (1990) examined whether the age-related increase in body size of young swimmers (mean age at the start of the study was 12.9 years), would cause increased water resistance and hence might require greater propulsive forces at equal velocities while swimming. During a period of 2.5 years the children showed significant increase in height and weight. The body cross sectional area increased by 16 percent. However, the drag did not change (30.1-30.9 N) at a constant 1.25 $m*s^{-1}$ speed. It was suggested that the change in height resulted in a more streamlined position of the swimmers, demonstrated by the decrease in Froude number ($\frac{V}{\sqrt{g \times H}}$), and thus in a decrease in wave-making resistance. Researchers therefore concluded that during growth a complex process takes place and different factors determine drag, among others: height and the shape of the body, changes differently, having opposite effects on drag.

1.7 Stroking characteristics and swimming economy

Swaine & Reilly (1983) used a protocol similar to Craig & Pendergast (1979) to produce the relationship between v and SR on a biokinetic swim bench. They determined also the oxygen consumption (VO_2) versus SR relationship. The purpose of their study was to investigate the consequences of altering the spontaneously chosen SR in all-out swimming on performance and metabolic variables, even though the exercises on a swim bench is completely different from real swimming. The results confirmed that freely chosen SR produced the top performance in swimming and the highest peak VO_2 values in simulated swimming on a biokinetic swim bench.

Costill & al. (1985) studied the energy expenditure during front crawl in order to predict success in middle distance events. This study introduced a concept of stroke index (SI) which is the product of v and SL. The best predictors of VO_2max for trained swimmers were lean body weight (LBW) and SI (r=0.97). The single best predictor of performance in the 400-yd front crawl swim was SL (r=0.88), whereas the combination of SL and VO_2max ($ml*kg^{-1}$ LBW $*min^{-1}$) correlated 0.97 with performance during the swims. The findings of this study demonstrate the importance of stroke technique on the energy cost and variations in performance during competitive swimming.

Weiss & al. (1989) made an attempt to evaluate the influence of a swimmer's biomechanical behaviour on aerobic and anaerobic energy requirements. A total of 43 elite female swimmers were studied with a testing protocol similar to earlier presented by Simon & al. (1982). SL was observed to decrease with the increase in both v and SR. The increase in SR and the decrease in SL were related to v in a linear manner up to the anaerobic threshold. With the onset of blood lactate accumulation, the stroke was shortened and the swimmers required a higher stroke frequency. It was concluded that both the aerobic and anaerobic capacity may play an important role in maintaining optimal swimming technique.

Toussaint (1990) studied two groups of endurance trained athletes, competitive swimmers and triathletes, who differed in their swimming performance significantly. The groups did not differ in gross efficiency , stroke frequency and work per stroke. Differences were found in distance per stroke and mean velocity of swimming. Toussaint (1990) concluded that triathletes should focus their attention on their swimming technique rather than improving their ability to do more work. The distance per stroke (SL) was suggested to be used as a criterion to evaluate skill improvements in swimming.

Recently, Johns & al. (1992) investigated the specific influences of taper, independent of possible shaving effects, upon factors associated with swim performance in twelve male swimmers. The taper was performed prior to the swimmer's season ending meet. On the one hand, all subjects improved their performance times significantly. On the other hand, SL was slightly different between the two groups of swimmers (better and worse) but taper did not result in statistically significant alterations in SL in either groups. No changes in SR were observed. However, the SL increased during the submaximal swim by 5% with body hair removal, and also the SR was significantly reduced with shaving. No alterations in estimated oxygen consumption and post-exercise BLa levels were observed with taper but BLa was lower in better swimmers at the pre-taper testing session. Better swimmers had slightly higher power outputs as compared with worse ones. All swimmers improved their peak power by 5 % with taper but shaving did not produce a further increase in power-generating ability.

1.8 Biomechanical performance in other sports

Several studies have been conducted to determine relationships between the physical characteristics of runners and their preferred- and presumably optimum combination of stride length and stride frequency (Rompotti, 1957; Hoffmann 1972; Cavanagh and Williams, 1982). Ballreich & Gabel (1975) listed five possibilities of gaining advantage in a sprint running race: (1) Longer SL with constant SR, (2) higher SR with constant SL, (3) longer SL with higher SR, (4) longer SL with relatively lower SR, and (5) higher SR with relatively lower SL. The ideal would be the third alternative, but it is only possible with very high performance capacity. Elliott and Blanksby (1976) noticed that in general the velocity increases with the decrease in SL and increase in SR. Nelson & al. (1972) observed that when the velocity increased over 5 $m*s^{-1}$, SL was increasing with the decrease in SR. Luhtanen & Komi (1978) demonstrated that with the increase of velocity even over 7 $m*s^{-1}$, both the SL and SR were noticed to increase. However, Frishberg (1983) observed no change in SL with the increasing velocity while sprinting.

It has been suggested that the manipulation of biomechanical variables may be one of the factors through which the running economy can be altered. Högberg was the first to document that SL variation from that which was freely chosen by a runner resulted in an increase in sub maximal oxygen consumption. Also Knuttgen (1961) observed that when SL has been changed from the normal, the oxygen uptake will increase. Högberg's investigation was replicated by Cavanagh & Williams (1982) with a larger sample size. They found that runners were most economical at their freely chosen SL and described overstriding to be less economical than understriding. They also observed no change in oxygen uptake when only minor enhancements were made in SL. When they calculated the percent value of SL from the leg length, it was noticed that SL cannot be related to leg length. Morgan & Martin (1986) investigated the effects of SL manipulation in race walking economy and found that trained subjects selected locomotion patterns that are nearly optimal in terms of aerobic demands.

Nelson & Gregor (1976) reported that the augmentation of running speed in long-distance runners depends mainly on incremental increase in SR as a result of an expanded training period. However, with the passage of time both the SL and SR were noticed to change. Improvement of running economy can theoretically be achieved by reducing the amount of external energy needed to overcome resistance. Bailey & Pate (1991) suggested that age, segmental mass distribution, SL and other biomechanical variables may play a significant role in determining external energy demand. SL and running economy have been shown to differ between experienced and novice runners, with experienced runners possessing longer SL and greater running economy. Therefore, it was hypothesised that with training a novice will develop a longer SL and greater running economy than that observed at the onset of training. Bailey and Messier (1991), however, found that neither SL nor running economy changed significantly over a seven-week training period in novice male runners. Therefore, it may be so that changes in SL and running economy take several months, if not years to develop.

Williams and Cavanagh (1987) investigated the relationships between running economy and a large array of biomechanical variables in trained runners. The results indicated that the most economical runners possessed a significantly lower force peak at heel strike, greater shank angle with the vertical at heel strike, smaller maximal plantar flexion angle following toe off, greater forward trunk lean, and lower minimum velocity of a point on the knee during foot contact. They also reported that 54% of the variation in running economy could be attributed to variation in biomechanical variables. It was suggested that it may be possible to systematically vary aspects of an individual's running style with an ultimate goal to modify selected variables on a more desired level, precipitating an improved running economy.

In cross-country skiing, it has been found that the diagonal skiing performance is strongly influenced by a skier's SL. For example, Dillman (1979) suggested that in uphill skiing, the skiers should concentrate on increasing SL more than SR. Smith & al. (1988) studied the techniques of elite male skiers skating up a hill in World Cup competitions by high speed filming. The skiers were noticed to skate about the same tempo. The significant correlation of cycle length with velocity (r=0.85) emphasises the importance of cycle length for ski skating racers also.

1.9 Summing-up

It seems surprising that there have been only a few studies concerned with obtaining a clear understanding of the relationships among SL, SR and v. There is an agreement among investigators that the mean SR for free style, butterfly and breaststroke are very similar, and that differences in SL determine the differences in the v attained. For some reason, the mean SR in the backstroke is considerably less, and the SL somewhat greater, than in the other strokes. Furthermore, there is an agreement that the greater stroking speeds attained by male swimmers, compared to females, are primarily due to correspondingly greater SL, the SR values being very similar in general.

The investigators seem to agree that as the distance of the race increases, the SL increases (except in the butterfly stroke), while the SR and v decreases. There is also an agreement concerning how SL, SR and v vary as a race progresses. Except for finishing bursts in the final 1-2 laps of distance events, SL and v generally decrease throughout the course of a race. No similarly consistent pattern has been found with respect to SR. In some instances, it decreases, in others it remains essentially constant, and yet in others it actually increases, as the race progresses.

The comparisons between elite and less good swimmers in SL, SR and v show that the differences in v are due primarily to differences in SL. As a group, fast swimmers have greater SL than less-fast swimmers. In addition, the anthropometric variables seem to have a major effect on SL and consequently on the ability to swim fast.

Hay (1987) discussed the general confusion related to stroke performance:

> "Studies of SL and SR often appear to be very confusing because the results obtained in one often appear to be exactly opposite of those obtained in another. Thus if one notes how swimmers increase speed when moving down from 200 m to 100 m; usually by increasing SR and decreasing SL; one might conclude that the emphasis in training should be on increasing SR and decreasing SL. Then, if one examines the difference between a group of fast swimmers and a group of not-so-fast swimmers and notes that the faster group have longer SL, one might conclude that the emphasis in training should be on increasing SL. Some exceptions aside, the truth of the matter appears that (a) to increase Speed in the short term (for example, at the finish of a race), one should strive to

> increase SR, and (b) to increase Speed in the long term (for example, over the course of a season), one should strive to increase SL."

One thing, however Hay didn't account, was that it is not only the speed increase or decrease leading to either short term or long term adaptations, that may actually effect the stroke parameters. There may also be confusing changes in the stroke performance due to speed and intensity variations during the course of a single training session as well. These effects have not been discussed extensively before.

2 PURPOSE AND RESEARCH PROBLEMS

2.1 General purpose

The general purpose of the present study was to try to find answers to questions which are related to some of the fundamental problems among swimmers and coaches:

- Why are the techniques of swimmers so variable during both competition and practice?
- Why are their techniques continually changing during practice?
- Is it possible to measure technique performances in order to follow their development in swimming skills.

More specifically, this study tried to find answers to those questions by examining the effects of variable swimming conditions on the relationships among stroke parameters during training, and by making comparisons with the known facts about competitive situations. Special interest was focused on investigating the effects of the enhancement in swimming intensity on stroke parameters and their interrelationships.

Study I was designed to evaluate the stroke performances in free style swimming by measuring mean velocity (v), stroke rate (SR), and stroke length (SL) in three different intensity levels during aerobic/anaerobic loading. Study II aimed to examine the interrelationships between v, SR, SL, stroke index (SI), and blood lactate concentration (BLa) in different types of exercises of varying distance and duration. The intention of study III was threefold: (1) to examine the relationships among the stroking characteristics during short maximum swims; (2) to study the relationships of some anthropometric variables and biomechanical performance; and (3) to study the relationships between maximum tethered force and maximum performance in the water. The aim of the study IV was to examine the interaction between stroke technique and performance capacity during a fitness test. Study V was designed to make comparisons among the biomechanical parameters between normal crawl and crawl arm stroke swimming. The purpose of Study VI was (1) to examine the differences in the relationships among the stroking characteristics between the laps during swimming exercises; and (2) to examine whether these relationships would change in relation to enhancement in swimming intensity during aerobic/anaerobic loading.

2.2 Research problems

Based on the major goals of the study the objectives have been summarised in the form of the following questions:

(1) How does the initial stroking strategy among the stroke parameters in training conditions correspond to those in competition?

(2) How does the initial stroking strategy among the stroke parameters change when there is a change in swimming intensity during training?

(3) How does the stroking strategy change between different swimming distances during training sessions?

(4) How does the stroking strategy change between successive pool lengths during the course of a training session?

(5) How does physical conditioning effect stroke performance during training?

(6) How does the different modes of crawl swimming effect stroke performance during training?

(7) What is the role of selected anthropometric variables on the stroke parameters during training?

3 METHODOLOGY

3.1 Design and testing procedures

A 50-m long indoor swimming pool with standard water temperature of 26-27°C was used to arrange the different aerobic/anaerobic loading situations of free style swimming. The six original studies included five different procedures commonly used for testing and/or normal training practice as well. Table 1 lists the protocols used during the entire project.

In studies I, II and IV, a set of ten to fourteen 100-m swims (protocol A) was performed with the velocity increased progressively from low to maximum according to guidelines reported by Gullstrand and Holmer (1980). In study V, two exercises were performed with a similar (15*100-m) procedure, but with a different starting time than the previous one. In protocol A, the swimmers were instructed to employ an even pace during the 100-m swims and to increase speed by about 1.5-2 s/5 s after each swim. Before getting started the swimmers were allowed to do warm-up swimming for about 10-15 minutes and the predetermined starting velocity was practised by performing two or three 100-m swims successfully with that pace. The warm-up procedure was similar to all incremental type of exercises (protocols A, B and D). In study V the subjects carried out two sets of fifteen 100-m swims: by normal crawl swimming (CN) and by crawl stroke with arms only (CA). In CA swimming, pull-buoys between the legs with ankle ties were used to inactivate the lower extremities in a conventional manner. The two sets were conducted on separate days, one rest day in-between. The order of the performances was randomised so that four subjects carried out CN before CA and vice versa.

TABLE 1 Summary of the testing arrangements during the experiments.

Protocol A Studies: I; II; IV; V	10-15* 100-m swims (Gullstrand & Holmer, 1980) progressively increasing velocity with 1-min rest between swims (a) starting time 25 s + best time in 100-m swim (I; II; IV) - speed increase by 1.5-2 s per 100-m swim (b) starting time 2:00 / 5 s increment per 100-m swim (V) *blood samples 20-40 s after swims + 3, 5, 7, 10 min at the end measurement of time and stroke parameters in each pool length
Protocol B Study: II	5-6*300-m swims (Simon & al., 1982) progressively increasing velocity with 1-min rest between swims starting time 4 min 30 s / 15-s increment per 300-m swim *blood samples 20-40 s after swims +3, 5, 7 min at the end measurement of time and stroke parameters in each pool length
Protocol C Study: II	2*100 and 2*400-m swims (Mader & al., 1976) first reps at moderate and second reps at maximum pace 20-30 min rest between swims; 1 hour between the sets *blood samples before and 1, 3, 5, 7, 10 min after each swim measurement of time and stroke parameters in each pool length
Protocol D Study: VI	5-6*400-m swims progressively increasing velocity with 2-min rest between swims starting time 120 s + best time in 400-m / 20-s increment/400 m *blood samples 20-40 s after each swim and 3, 5, 7 min at the end measurement of time and stroke parameters in each pool length
Protocol E Study: III	3*10-m free swim and 3*15-s tethered swim in randomised order maximum efforts with full recovery between swims measurement of time and stroke parameters in each swim measurement of maximum tethered swimming force (fig. 2)

*) Pre-exercise blood samples after warm-up swimming in protocols A-D.

In protocol B, the instructions of Simon & al. (1982) were followed, and the number of repetitions, starting times and velocity increases during testing were chosen according to their suggestions. On the other hand, this protocol was very similar to that of the A mode's. Protocol D followed closely similar principles and pacing as the B mode. In study VI, each of the subjects performed a set of five to six even-paced 400-m swims. The velocity was progressively increased with a time decrease of 20 s by each successive effort and with about two min breaks for blood sampling in between. The starting time was set so that the swimmers were asked to estimate their best performance in 400-m distance during the set. The starting time was calculated by adding 120 s to this estimate. In addition, one or two days after the 400-m efforts, a set of two 100-m swims was performed using a protocol described earlier by Mader & al. (1976).

Protocol C, "the two speed test", has been introduced by Mader & al. (1976). This test mode consisted of two separate test series with two different velocities in both of them. The pace for the first repetitions were about 80 percent of previously observed maximum at that particular distance and the second ones were performed with maximum pace. Protocol E included two different maximum intensity exercises: (a) three 10-m swims preceded by 10 m for speed acceleration up to maximum, and (b) three 15-s tethered swims. Both exercises were performed in randomised order during the same training session and allowed full recovery between the repeated swims. The median time performance of the three trials in both cases was chosen for further analysis of maximum velocity and other parameters. The procedure for the tethered swimming trials will be described later in chapter 3.5.

The studies which combined data obtained by different protocols, had to consider some additional factors affecting the results. Among them, the effect of testing order. To avoid this influence, the order of the occurrence of the trials was randomised in every case. For example in study II, a group of 11 swimmers performed the four sets of exercise in randomised order during a one week period. At first, twelve different choices were arranged, and each of the eleven subjects had to perform the testing in one of those choices. One remained unused because of a failure to complete the testing in one subject. During the course of the experimental week the subjects did their daily training programs also between the test days but with reduced intensity and total volume of training. The heavy weight training was abandoned for a while but the circuit weight training with light weights and stretching exercises was carried out as usual. These same principles were followed also in the studies III and V which made comparisons between two different sets of exercises.

3.2 Subjects

The subjects were 87 well-conditioned male competitive swimmers, representing five different samples, taken to participate in the six original studies. Table 2 presents the five groups with varying numbers of participants. Study IV includes three sub-groups.

The rights and privileges of the subjects were respected in accordance with World Medical Association Declaration of Helsinki. The subjects were interviewed by the investigator in order to reveal any kind of malfunction which might risk their healthy status during the physical loading. A detailed information was given about all of the risk factors which might be connected with the experiments, before the subjects gave their consent to serve as subjects in each of the six original studies separately. One of the prerequisites was that the swimmers should be able to perform the exercises designed for these studies, and it was also a must for a subject to be prepared to execute ultimately strenuous and exhaustive training sessions throughout the entire projects. The swimmers were active members of competitive swimming teams at the time of the measurements, representing medium to top level performances at their age groups or senior level. The fact that all of the subjects had been participating in competitive swimming and regular training for several years, enabled their attendance and reduced the danger of hurting themselves during the examinations. The subjects for the study IV were selected according to their participation in physical conditioning tests during the course of regular training, representing three different fitness categories, as shown by the table 2.

TABLE 2 Means, standard deviations (S.D.) and coefficients of variation (CV) of the subjects for age, stature, body mass and best competition time in short course 100-m front crawl swim.

	Study (nb)	N (nb)	Age (y)	Stature (cm)	Mass (kg)	Time (s)
Mean	I; II	11	19.5	182.7	71.6	56.0
S.D.			3.5	6.5	6.0	2.3
CV			17.9	3.6	8.4	4.1
Mean	III	33	17.9	176.9	66.9	59.6
S.D.			3.7	10.2	13.2	5.0
CV			20.7	5.8	19.7	8.4
Mean/1	IV	15	19.4	183.5	72.7	55.0
S.D.			2.9	5.6	6.2	1.3
CV			14.9	3.1	8.5	2.4
Mean/2		15	17.4	177.7	67.5	57.7
S.D.			1.9	5.5	5.3	1.4
CV			10.9	3.1	7.9	2.4
Mean/3		15	15.7	177.4	69.8	60.5
S.D.			1.3	5.1	9.1	1.4
CV			8.3	2.9	13.0	2.3
Mean	V	8	21.0	184.3	73.0	55.1
S.D.			2.4	4.0	5.8	1.7
CV			11.4	2.2	7.9	3.1
Mean	VI	10	19.9	184.4	77.1	54.9
S.D.			2.4	4.1	4.9	1.5
CV			12.1	2.2	6.4	2.7

Furthermore, the subjects represented different competitive strokes. Each of them, however, had been actively competing also in front crawl even if it was not their major stroke. The selection of crawl swimming instead of any other mode was based on its generality as the most commonly used stroke in swimming training. All of the subjects represented a more or less pure six-beat variant of the front crawl style which is typical, especially for sprint and middle-distance freestylers.

There were also some other major concerns which had to be considered before the start of the experiments. The most important one was related to the subjects' participation in regular training, which was not to be excessively disturbed. Therefore, the execution of the testing had to be synchronised with their training routines. Additionally, in some rare occasions, the training programs had to be organised differently than planned so that the high intensity experiments could be performed undisturbed during the examinations, and the high intensity workouts could be performed properly during the weekly training sessions. On the other hand, the experiments were closely similar to many of the workouts commonly applied for training and therefore could be used as the elements of the entire training practice as well. In accordance with these considerations, the training season which preceded the major summer competitions was considered as the most suitable one for the purposes of all six projects. While it was necessary to allow decently long rest periods in between the exercises, one or two days was considered as an appropriate time for recovery from one trial to another (studies I, II, V, VI). This was handled so that the day preceding the exercises, in all of the cases, allowed rest with aerobically paced swimming and with no heavy strength training in close proximity.

3.3 Measurement of stroke parameters

Mean velocity of swimming (v), stroke rate (SR), stroke length (SL) and stroke index (SI) as well as the duration of different phases of a stroke cycle were considered as the parameters for observing the stroking characteristics of swimming. The measured values represented either a mean of a certain distance (10, 100, 300, 400 m) or a mean of a 50-m pool length.

Mean velocity of swimming (v): Time to the nearest 0.01 s was measured for each of the swims with a digital stopwatch to obtain v ($m*s^{-1}$) during the experiments. The v was calculated as an average value for a predetermined distance. Split times for each 50-m swim were also obtained to calculate v for each of the pool lengths. No dive was allowed in starting in order to avoid additional high velocity in the early part of the swims. Maximum v (MV) in study III was obtained so that times for the three 10-m all-out swims, preceded by 10-m speed acceleration, were measured from the subjects' head crossing a 10-m line before the pool end until the touch to the wall at the end of swim. The swims were performed with full recovery between the trials. The median time was selected for further analysis of maximum velocity and other variables.

Mean stroke rate (SR): The elapsed time for ten complete one arm stroke cycles during about 35-m section of each pool length was obtained to the nearest 0.01 s, and used to calculate SR (stroke cycles*s^{-1}). In all cases the swimmers completed the ten stroke cycle distance without inclusion of a turn, which allowed an accurate estimation of SR. In study III, SR was measured during both free swimming (SR_f) and tethered swimming (SR_t) experiments according to time spent in 4-5 stroke cycles.

Mean stroke length (SL): The SL (m*$cycle^{-1}$) was calculated by dividing v by SR for each distance and pool length.

Mean stroke index (SI): The SI has been presented by Costill & al. (1985) as a measure of swimming economy. It is the product of v and SL (m^2*$cycle^{-1}$*s^{-1}).

Duration of the phases of a stroke cycle: The swims were video--taped underwater (Panasonic Industrial Video, 5.6 mm wide angle objective, 50 frames*s^{-1}) in order to be able to distinguish between the different phases of a stroke cycle (Studies I, II, III, VI). The camera was set stationary on the bottom of the pool (2.5 m deep) so that the arms could be seen clearly from about 30 m after the start end until about 5 m before the turning end of the 50-m pool. In order to determine the time spent in different phases of the stroke cycle, a digital time signal (0.01 s) was recorded on the tape. The stroke cycle was divided into four different time phases which were analysed for both arms separately from the videotapes: (1) Catch time, from the hand entry into the water until the exit of the opposite hand from the water, (2) Pull time, from the end of catch until the start of the extension movement in the elbow joint, (3) Push time, from the end of pull until the exit of the hand out of the water, and (4) Recovery time when the hand was out of the water.

3.4 Assessment of swimming intensity

In order to define the different levels of aerobic/anaerobic metabolism during the exercises, 50 µl of ear capillary blood was taken from hyperemisized earlobes after each of the swims. Table 1 describes the timing of the blood sampling. The blood samples were inserted into tubes containing percloric acid and deep-frozen before further analysis of blood lactate concentration (BLa). Shortly after the measurements had been completed, the BLa was analysed by using the enzymatic method of Biochemica Böhringer (Böhringer Mannheim, 1979).

The range of velocity was divided into five different categories according to BLa responses during the exercises. The first intensity category (IC_1) represented pure aerobic swims. It was based on the assumption that there wouldn't be significant stress on anaerobic lactacid metabolism when the BLa stayed around its initial lowest level during easy swimming. The category was changed into IC_2 when BLa started to slowly but irregularly increase above this initial level (Study V). It was considered that the so-called anaerobic threshold (AT) was reached when the increase in BLa became more vigorous, i.e. after 0.5, 1.5 and 2 $mmol{*}l^{-1}$ increase above the initial lowest level in 100-, 300- and 400-m sets, respectively (Keskinen & al., 1989). The AT has commonly been used as a reference for endurance training and especially training for swimming economy. The values greater than this threshold level belonged to the third intensity category (IC_3), AT being the lower limit.

The fourth intensity category (IC_4) was reached at medium high BLa levels. In the 100-m sets the lower limit was set at BLa of 8 $mmol{*}l^{-1}$. In 300- and 400-m sets the corresponding limit was set to the point where BLa versus V curve was observed to reach linearity at medium to high levels of BLa. The upper limits for IC_4 were the maximum performances in 100-400-m distances. The fifth intensity category (IC_5) was represented by the all-out sprints in the 10-m swims.

3.5 Measurement of force production while swimming

Maximum force (MF) was measured during tethered swimming (figure 1) lasting about 15 seconds from the start of the measurement. An elastic cord from the subject's belt was attached to a strain gauge force dynamometer. The subjects tightened the cord by easy swimming and after the starting signal began to swim as hard as possible. The highest value (N) which was found in about 5-10 s after the start, was called MF in swimming. The force meter was calibrated before the measurements by hanging external weights (5, 10, 15, 20 kg) from the dynamometer in order to verify that the weights were displayed correctly by the force meter.

3.6 Measurement of anthropometric variables

The total length of the body (TL) was measured while subjects were lying on their back with their upper extremities extended above the head and, ankles plantar flexed. The width of abducted arms (AS, arm span) was measured between right and left arm from the fingertips. Standing height (H) and body mass (M) were measured by conventional methods. The AS:H-index was calculated to demonstrate the arm span versus stature relationship of a swimmer. The density of the body was estimated by skin fold thickness measurements from seven different points and from both sides of the body (Jackson & Pollock, 1978). The percentage of fat was calculated according to body density by Siri's formula (Siri 1961).

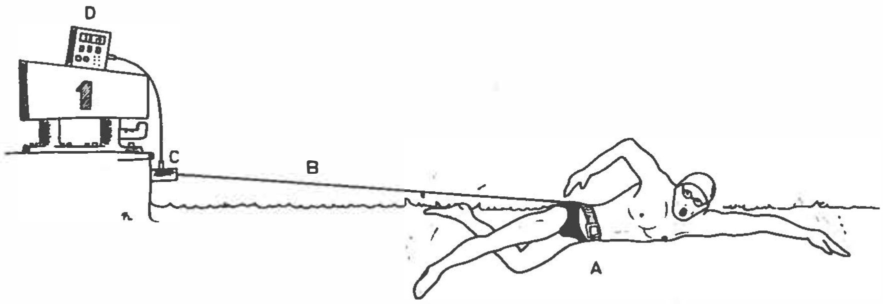

FIGURE 1 Measurement of force production while swimming. Symbols: A=belt, B=elastic cord, C=strain gauge, D=force dynamometer.

3.7 Analytical techniques

Data Analyses: In order to be able to make comparisons between the studied exercises and subject groups, the individual curves for the measured parameters were averaged. The averaging of the data was handled so that at first BLa values were plotted against v values and individual diagrams between BLa and v were drawn. Then the lowest level in BLa during the exercises was defined and the highest v at initial BLa level (I-point) was chosen as a common reference point to observe the changes in BLa (ΔBLa). Thereafter, the parameters (v, SR, SL, SI, BLa) were averaged according to changes in ΔBLa in individual diagrams and in each of the testing conditions separately.

Statistical analyses: After the data for each swimmer from various measurements had been collected, a series of statistical calculations were performed using computerised Survo-84 data files (Mustonen, 1987). The conventional statistical methods were employed to calculate the means and standard deviations for all measured variables. The coefficient of variation was computed where appropriate. Statistical analyses were performed to determine the inter-correlations among the variables. Regression analyses were conducted between SR, SL, v and BLa for the measurements and separately in different intensity categories. Other factors included the differences of the variable means between the exercises (Studies II and V), intensity categories (Studies I and VI), subject groups (Study IV), swimming distances (Studies II and VI), and pool lengths (Study VI). T-statistics with paired observations was used to test the significance of statistical differences in each of the conditions. To determine the statistical significance, the computed values were compared with critical values at $P=0.05$ level.

The reliability of the measurement of stroke parameters: In order to evaluate the reliability of the measurement of SR and consequently SL and SI, a series of measurements were performed by two experienced examiners, unaware of the results of the fellow examiner. Twelve swimmers performed ten swims each, at different intensities from very slow up to maximum. In a sample of 120 swims, the two series of times taken from ten one-arm stroke cycles, demonstrated no significant difference ($t=0.249$; $P=0.598$) and a very high correlation coefficient ($r=0.993$; $P<0.001$) between the two samples. The largest difference was 0.25 s while the average values (15.65 and 15.66 s), demonstrated very minor mean difference (0.01 s). The coefficient of variation within the two samples of analyses were identical (24.4 and 24.6 percent). The large variability demonstrated that the swimmers were swimming with very different stroke rates during the experiment, the measured times corresponding to SR values between 0.419 and 1.182 Hz.

Duplicate determinations in 212 swims were performed in order to evaluate the reliability of the measurement in the duration of the cycle phases from the video-tapes. The comparisons demonstrated no significant difference ($t=0.239$; $P=0.5944$) and a very high correlative connection ($r=0.981$; $P<0.001$) between the two analyses of the duration of the underwater stroke. The variability of the phase duration times in underwater and above-the-water stroke phases varied between 15.7 and 21.1 percent, respectively.

4 RESULTS

4.1 Initial stroking strategy

The data consisted five different samples taken from totalling 87 subjects. Each one of the tests which the subjects performed during the experiments were analysed individually. This means that the results were applied to training purposes shortly after the measurements had been completed. Thereafter the materials were organised in the six studies as presented in the preface of this thesis. Figures 2 and 3 demonstrate how the testing results were presented to the swimmers and their coaches. The examples have been taken from one subject after performing a set of eleven 100-m swims, according to the protocol presented earlier by Gullstrand & Holmer (1980). Anaerobic Threshold (AT) was estimated at approximately 1.39 $m*s^{-1}$ (72 s/100 m) speed, corresponding to a $\Delta 0.5$ $mmol*l^{-1}$ increase in BLa above the initial lowest level. SR demonstrated a continuously increasing pattern (fig. 2) while SL values showed more complex relationships with v. In fig. 2 and 3, the SL values stayed at their constantly high levels in the early phase of the exercise. After the AT level was reached, the exercise became more and more anaerobic as seen in continuously increasing BLa; meanwhile the SL was decreasing. However, all swimmers did not necessarily follow this pattern, but instead demonstrated a continuously decreasing SL. The pattern changed in relation to aerobic/anaerobic metabolism so that under the AT, the decrease in SL was linear, and after AT, the reduction became more rapid (SL collapse). Some swimmers increased their SL in the early phase of the set and after the AT level was reached, the SL curves started to decrease. This information could be used to help the swimmers to find the most appropriate number of strokes per lap when training at around the aerobic/anaerobic transition.

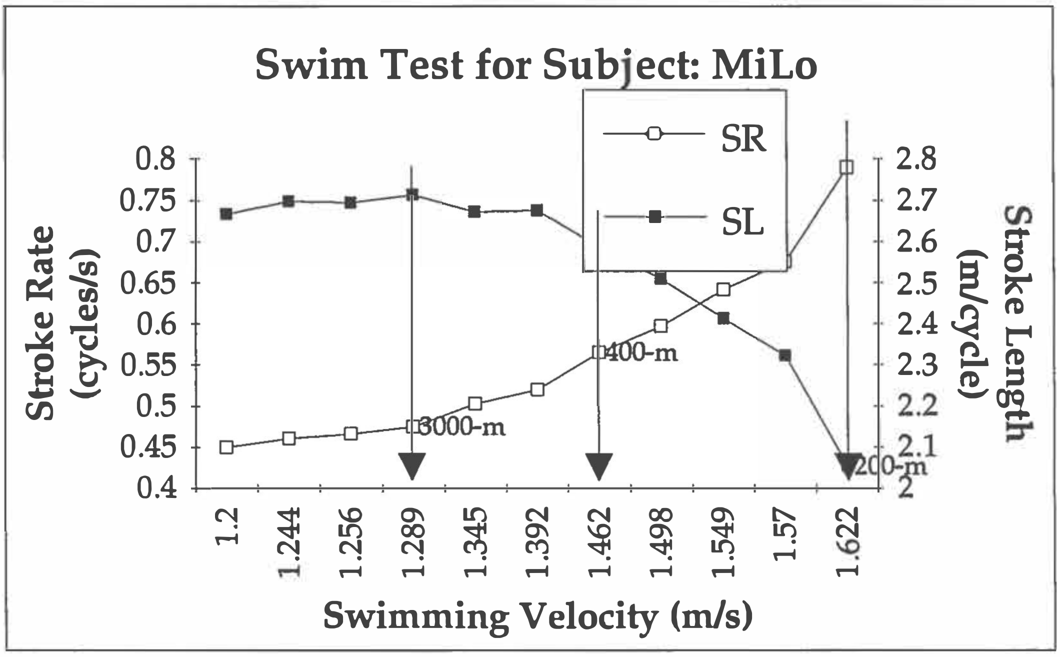

FIGURE 2 An example of a test result handed over to the swimmers participated in a testing session for physical conditioning and technique. The arrows indicate the maximum performance velocities in 3000-m, 400-m and 200-m swims.

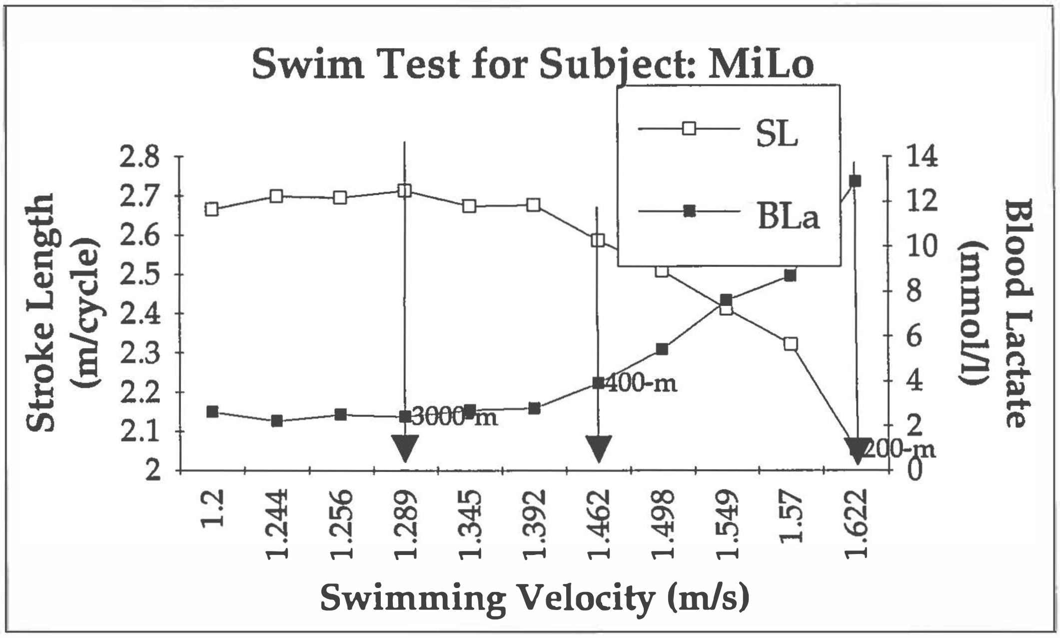

FIGURE 3 An example of a test result handed over to the swimmers participated in a testing session for physical conditioning and technique. The arrows indicate the maximum performance velocities in 3000-m, 400-m and 200-m swims.

The data were analysed so that the relationships among the different stroke parameters could, on one hand, be examined for all of the data separately in the six original studies and, on the other hand, for the different swimming conditions correspondingly in each of the cases. The results demonstrated that the overall relationships between v, SR and SL in variable exercise conditions followed similar behaviour as has earlier been observed in different competitive swimming situations (East, 1970; Satori, 1974, 1975, 1976, 1980; Craig & Pendergast, 1979; Hay & Guimares, 1983; Craig & al., 1983; Pai & al., 1984; Craig & al., 1985; Kennedy & al., 1990; Wakayoshi & al., 1992).

Thus, the data of the six original studies when combined with the results previously obtained from competitive situations elsewhere, can be considered as the normal biomechanical stroking pattern, i.e. the initial stroking strategy to produce speed during training. This strategy consisted of significant non-linear relationships between v, SR and SL. This means that the increase in v was produced with the increase in SR while SL was decreasing. When the results of the four sets in study II were put altogether, a significant positive correlation (r=0.86) was found between v and SR, while negative correlation coefficients were detected between v and SL (r=-0.44) and between SR and SL (r=-0.83).

4.2 Stroke parameters and enhanced swimming intensity

The initial stroking strategy was used as a reference when the comparisons were made between the five intensity categories (IC_1 to IC_5). Study II (see table 1) made comparisons between different exercise modes and study VI examined the stroking characteristics between the laps during exercises at intensities from IC_2 to IC_4. Studies I and IV examined the incremental type of exercises using a set of 100-m swims with the intensities varying from well below the anaerobic threshold (AT) until exhaustion (from IC_2 to IC_4). Study V included the pure aerobic paces (IC_1) also, otherwise with practically identical design. Study III examined IC_5 swims only.

The results showed that the v, SR and SL changed with the enhancement in swimming intensity and the five intensity categories were characterised by different relationships among the stroking parameters. Figure 4 demonstrates the changes between IC_2 and IC_3 - IC_4 in v versus SL relationship in four exercises. Figure 5 shows the same situation in v versus SR comparisons. The intensity categories correspond to velocities as presented by figure 6 (IC_2=low; IC_3=medium; IC_4=high). The early part of both the n*100-m (solid line) and n*300-m (dotted line) curves (figure 4) remained at constantly high levels with no change in SL along with the increase in swimming speed. SL started to decrease at around AT level (lower limit for IC_3) and thereafter the relationship between v and SL became similar to the initial strategy. The relationship between SR and v demonstrated only minor variation between the tested exercises, and the relationship remained closely similar to the initial strategy also during the IC_2 swims (figure 5).

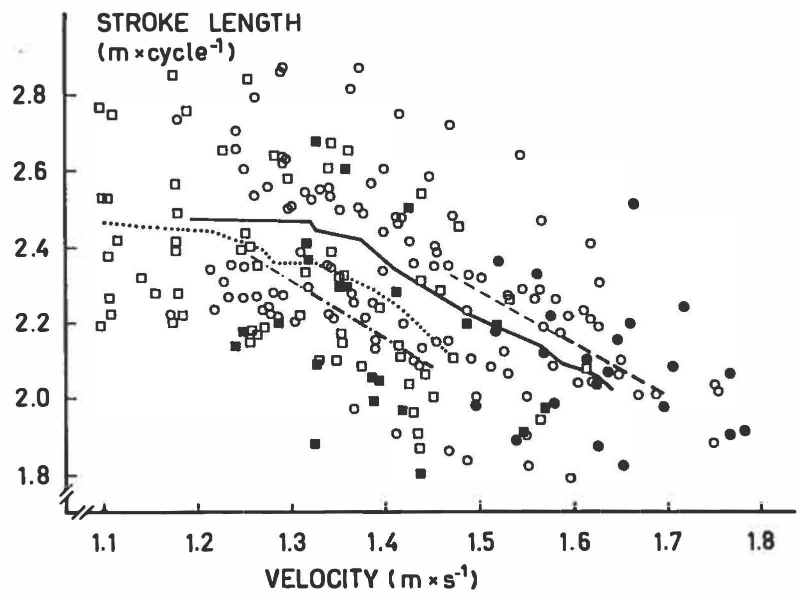

FIGURE 4 Averaged curves for swimming velocity and stroke length in four exercises. Symbols: n*100-m=solid line, open circles; n*300-m=dotted line, open boxes; 2*100-m=dashed line, filled circles; 2*400-m=dotted dashed line, filled boxes.

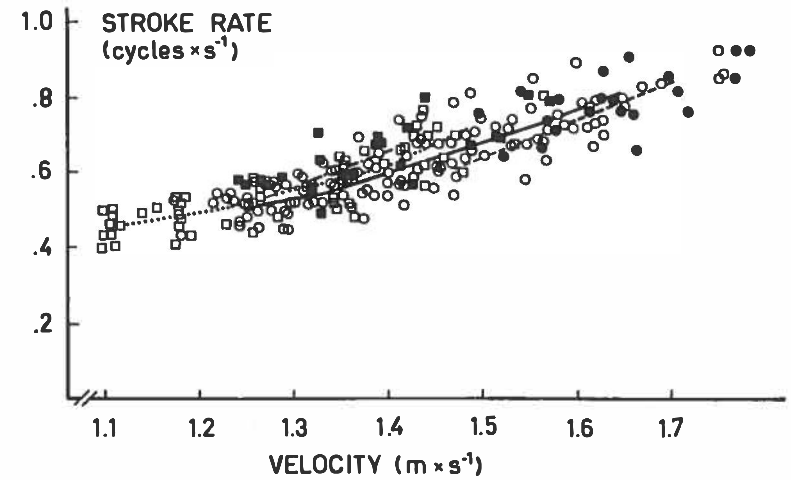

FIGURE 5 Averaged curves for swimming velocity and stroke rate in four exercises. Symbols: n*100-m=solid line, open circles; n*300-m=dotted line, open boxes; 2*100-m=dashed line, filled circles; 2*400-m=dotted dashed line, filled boxes.

When the intensity categories IC_2 - IC_4 were compared between each other in n*100-m exercise, it was shown that the stroking strategy was similar to the initial strategy at medium intensity swims (IC_3) only (figure 6). The situation was most interesting in IC_2 (low intensity) comparisons. The v versus SR relationship (figure 6A) demonstrated that there is a significant positive connection between the v and SR especially at IC_3 and IC_4 levels but negative, however non-significant, relationship at IC_2 level. SL demonstrated a statistically non-significant correlation with v at each of the studied intensity levels (figure 6B), but there was a positive connection, however non-significant, at IC_2 level.

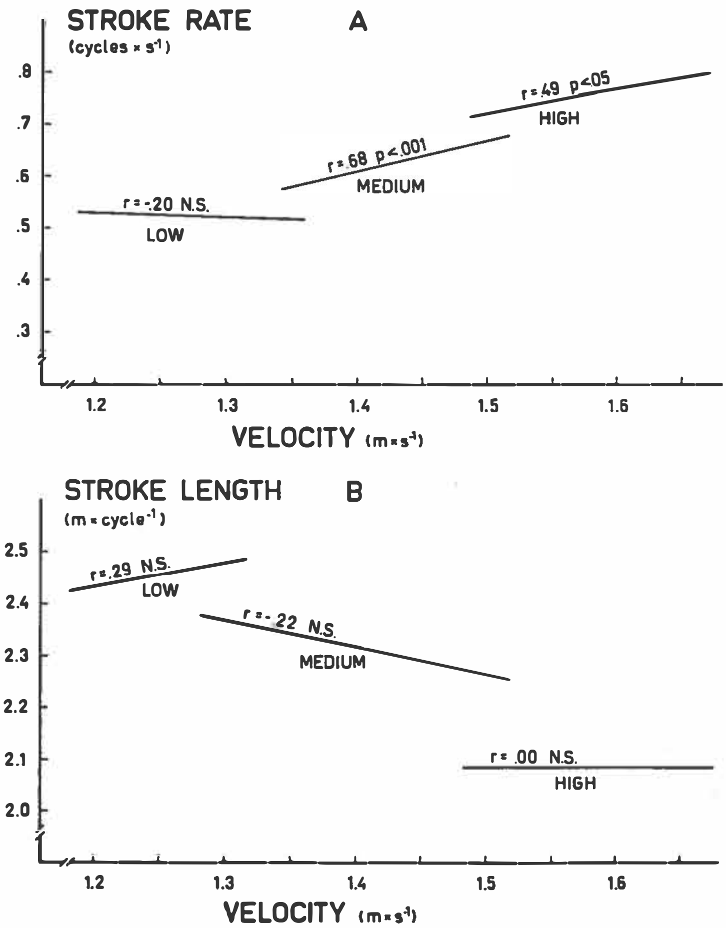

FIGURE 6 Linear regressions of swimming velocity in relation to stroke rate (6A) and stroke length (6B) at three intensity levels.

When the stroke parameters were related to BLa (figure 7), it was shown that the relationship between SR and BLa was positive, but statistically significant only for medium intensity (IC_3) exercises (figure 7B). Furthermore, the intensity level comparison showed that SL and BLa (fig. 7A) had a significant positive relationship in IC_2 swims, negative in

IC_3, but statistically non-significant relationship in high intensity (IC_4) swims. BLa, which in the total sample comparisons increased quadratically with an increase in swimming velocity, had the highest correlation coefficient value with v at medium intensity, and non-significant relationships at low or high intensity swims. As expected SR and SL had a significant negative relationship at all intensity levels separately.

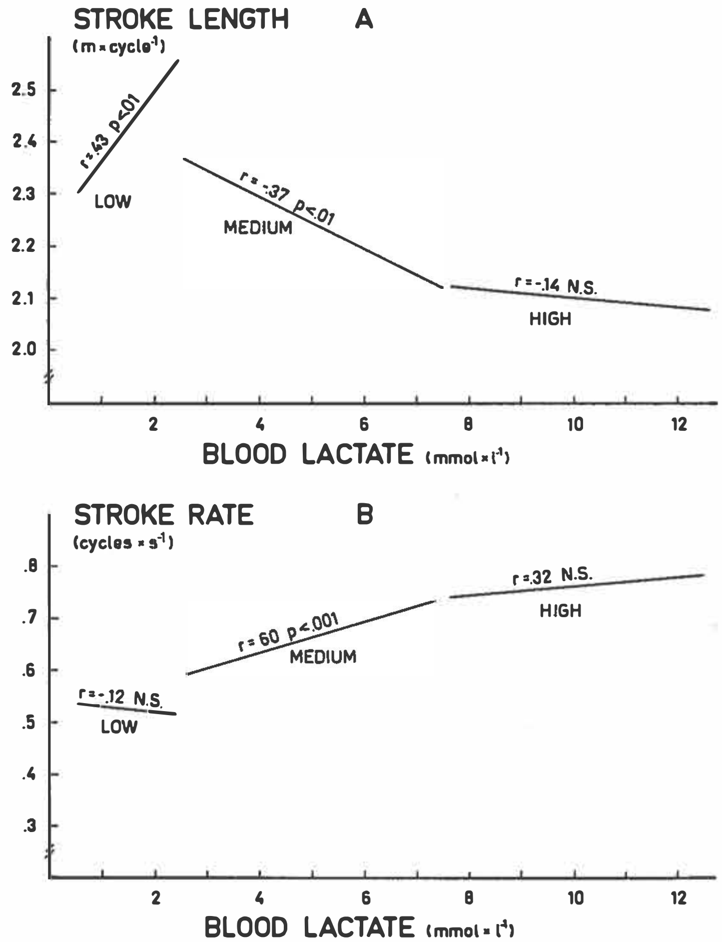

FIGURE 7 Linear regressions between blood lactate concentration in relation to stroke length (7A) and stroke rate (7B) at three intensity levels.

The v versus SL relationships were similar when compared between IC_1 (figure 8) and IC_5 (figure 9) swims, and between IC_2 and IC_4 swims (fig 7B). In figure 8 the IC_1 area can be seen between the S- and I-points. Thus, in both very low intensity aerobic and maximally paced anaerobic swims, the increase in v was produced mainly by the increase in SL with less emphasis on SR which, however, also increased continuously at IC_1. On the other hand, v and SL showed a statistically significant positive correlation (r=0.59) at IC_5, meanwhile the relationship between v and SR was negative and statistically non-significant (r=-0.19).

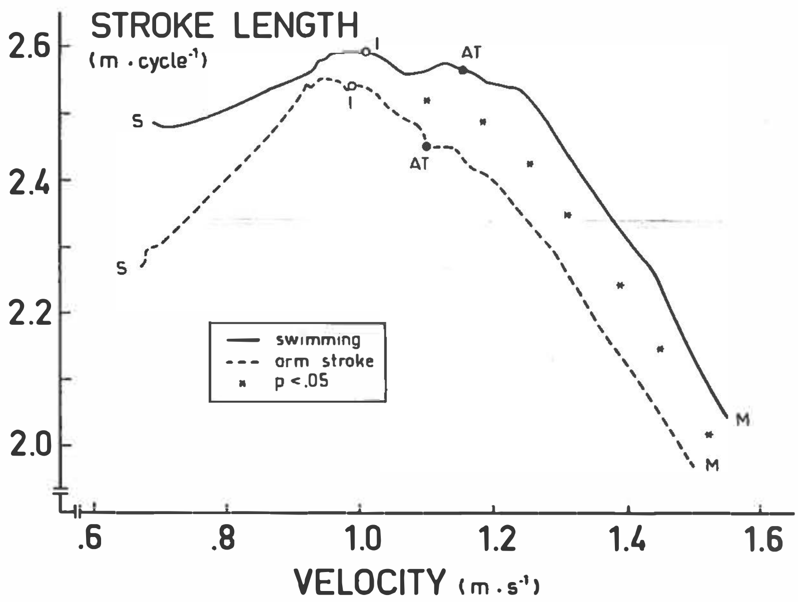

FIGURE 8 Averaged curves for swimming velocity versus stroke length relationships in CN and CA swims during 15*100-m exercise. Symbols: S=start, I=maximum speed at initial blood lactate, AT=anaerobic threshold, M=maximum.

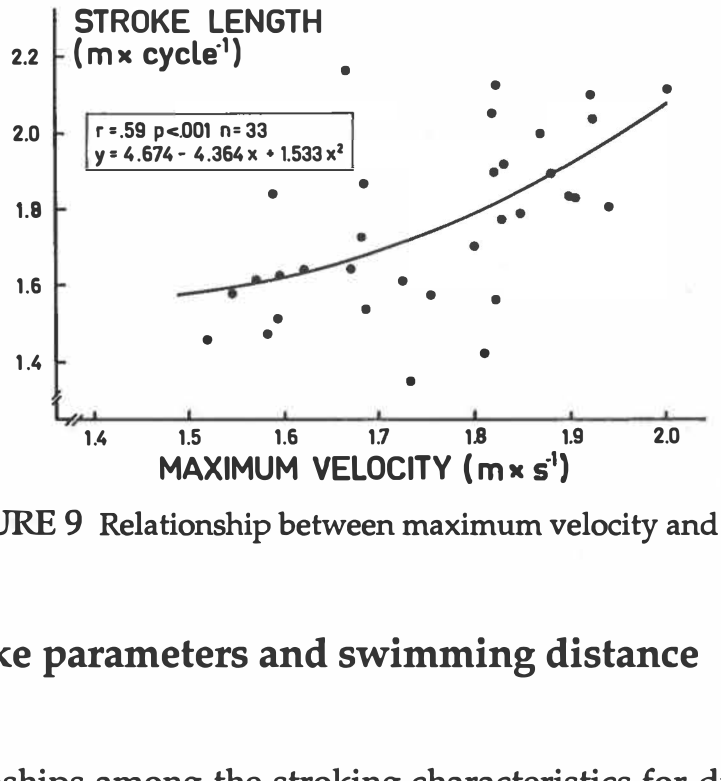

FIGURE 9 Relationship between maximum velocity and stroke length.

4.3 Stroke parameters and swimming distance

The relationships among the stroking characteristics for different swimming distances (100 m, 300 m and 400 m) as compared by study II, were similar to those presented in chapters 4.1 and 4.2 concerning both the initial stroking strategy as well as the data obtained from different intensity categories. However, as demonstrated by figure 4, the values were very different between the studied testing methods and swimming distances. Maximum SL values obtained at IC_2 level, i.e. velocities below the AT, were close to the same in n*100-m and n*300-m exercises. But shortly after the BLa started to increase above its initial level (IC_3), SL decreased with the increase in swimming speed and became different between the studied distances. SL decreased when the speed was increasing but the value of SL was distance dependent, having the shortest value when the distance was longest, in study II during the 2*400-m exercise. SL reached the lowest average values when the exercises were performed with n*100-m or 2*100-m modes, compared to n*300-m or 2*400-m modes. However, these differences as well as the difference in maximum SL were statistically non-significant. As demonstrated by figure 5, the SR was very similar between the exercises especially at IC_2 swimming. At IC_4 speeds SR was highest in the shortest distances, 2*100-m set being the fastest one. On the other hand, the lowest maximum values in SR were found in the 400-m mode as compared with the rest of the exercises.

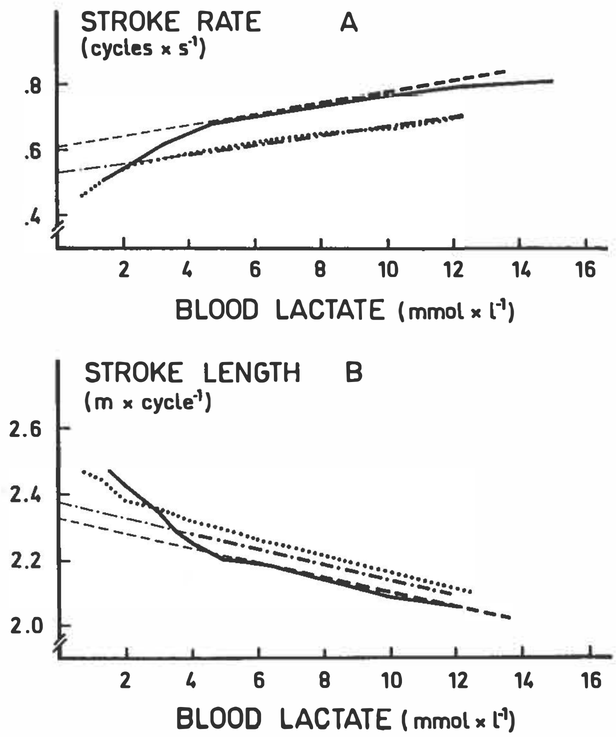

FIGURE 10 Blood Lactate concentration in relation to stroke rate (10A) and stroke length (10B) in four exercises. Symbols: solid line=n*100; dotted line=n*300; dashed line=2*100; dotted dashed line=2*400

BLa increased continuously with the increase in v, as expected. However, BLa versus v curves showed remarkably different metabolic demands between the exercises especially at higher swimming intensities (Keskinen & al., 1989). When BLa was compared with SR and SL (figure 10), it demonstrated opposite responses in the two relationships.

In SR versus BLa comparisons (figure 10A), the two stepwise protocols were very similar in low BLa-levels (IC_2 - IC_3) but from the 4-mmol*l^{-1} level on (IC_3 - IC_4), they became statistically different. No difference in SR was observed between the two 100-m sets, and between 300-m and 400-m sets, after the 4-mmol*l^{-1} level was reached. In SL versus BLa comparisons (figure 10B), the shortest distances were performed with shortest SL when BLa reached the 4-mmol*l^{-1} level. Stroke Index curves (not seen in the figures) confirmed the results detected by SL.

4.4 Stroke parameters and successive pool lengths

When the stroke parameters were examined during the course of an exercise consisting five to six 400-m swims (Study VI), the comparisons were made both between the eight laps (figure 11A, B, C) and between the curves drawn separately for the eight pool lengths and for SL (figure 12) and SR (figure 13).

A significant reduction in v, SL and SR was observed in the early part of the 400-m swims (fig. 11A-C.). These changes were parallel with the increase in the time duration of different phases of the underwater stroke between laps one and three. During the middle part of the 400-m swims (laps 3. to 6.), v and SR remained constant with only minor variations. However, the SL curve (fig. 11C) started to decrease throughout the 400-m swims when the AT-level was reached (IC_3) and the decrease became more pronounced towards the end of the exercise protocol (IC_4). During one or two of the last pool lengths the subjects could slightly increase their speed by increasing SR.

The first lap curves were noticed to be completely different from those of the seven others at all intensity levels. The laps 2-8 formed a family of curves with only minor differences between each other in both V versus SL (fig. 12) and V versus SR (fig. 13) comparisons. Lap number 2 became different from the rest of the curves at aerobic (IC_2) and maximum (IC_4) swims. The plots of the maximum 100-m swims (IC_4) were well in line with those of the 400-m swims. It must be added that the variability of SR and SL in each curve was similar (appr. 9 %). Thus for the clarity of presentation only the average curves are shown in fig. 12 and 13.

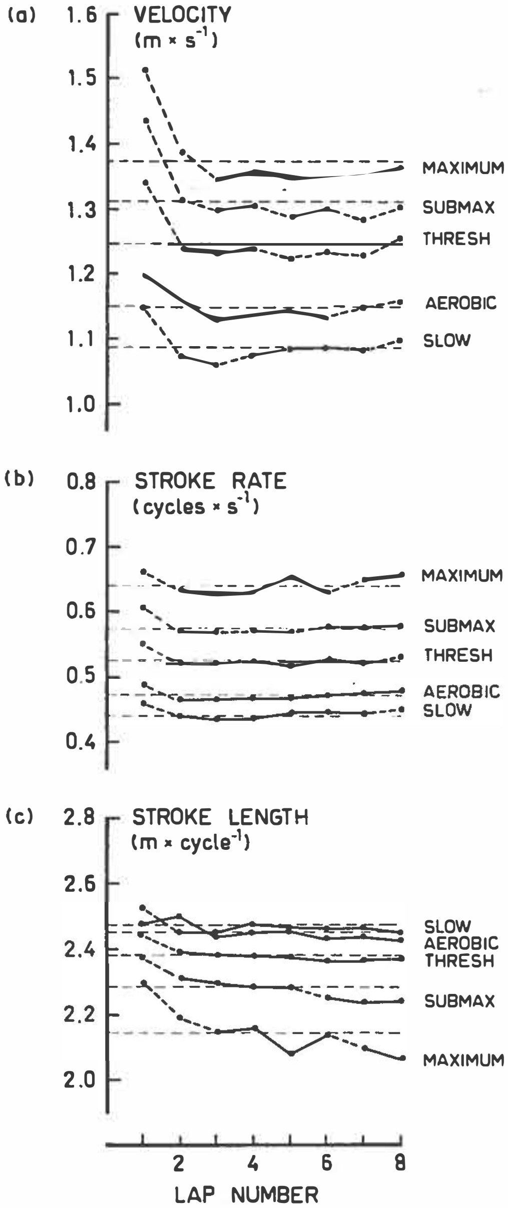

FIGURE 11 Velocity (11A), stroke rate (11B) and stroke length (11C) curves for eight pool lengths in five different intensity levels. Symbols: horizontal dashed lines=averaged values for the five intensity categories; solid line between two lap numbers=statistically non-significant difference between two points; dashed line between two lap numbers=statistically significant (P<.05) difference between two points.

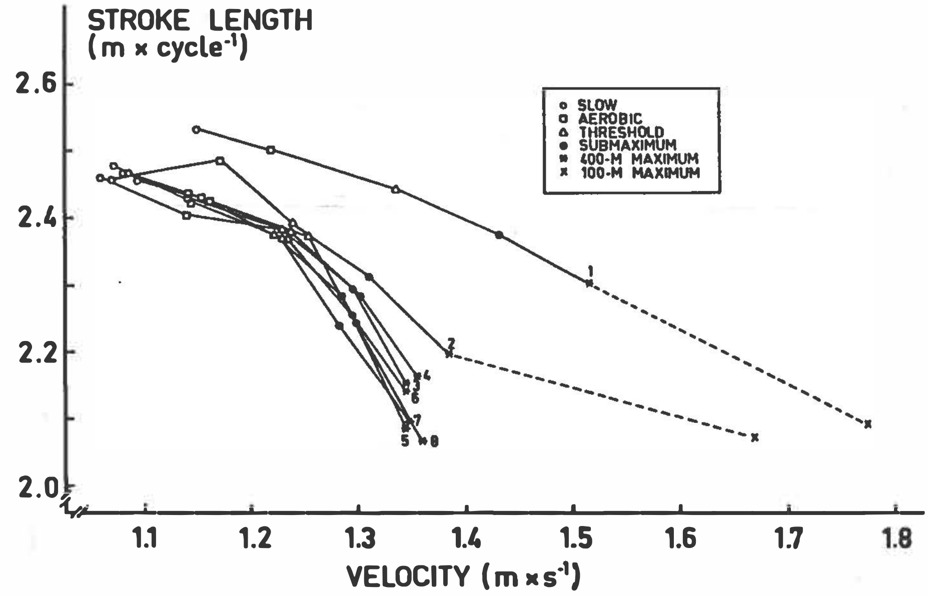

FIGURE 12 Velocity versus stroke length curves drawn separately for eight pool lengths in n*400-m swims complemented with plots of a maximum 100-m swim for two pool lengths. (The numbers within the curves indicate the pool lengths)

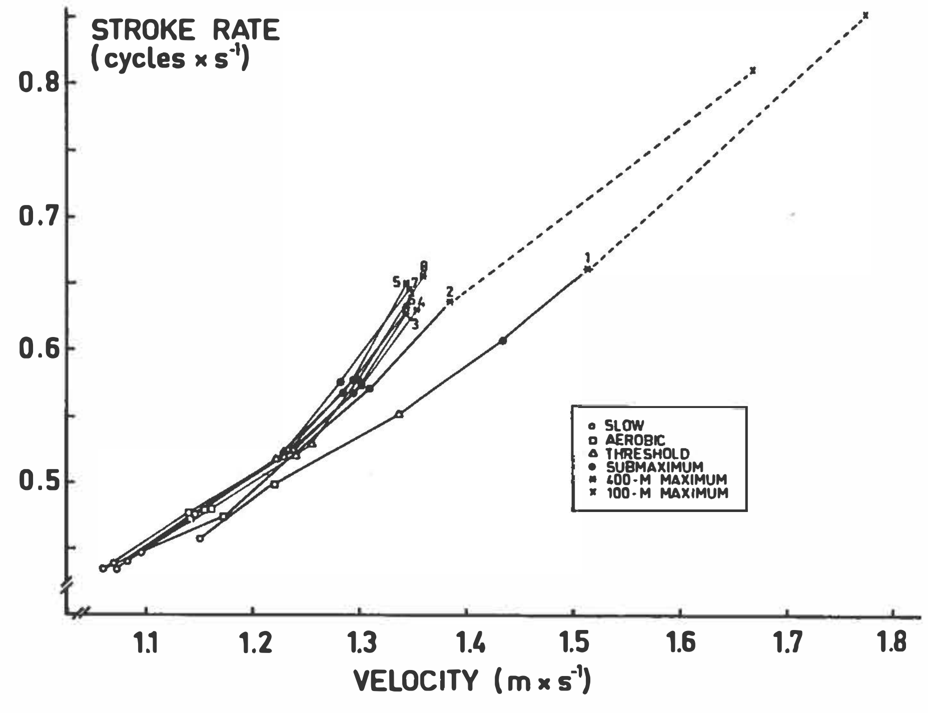

FIGURE 13 Velocity versus stroke rate curves drawn separately for eight pool lengths in n*400-m swims complemented with plots of a maximum 100-m swim for two pool lengths. (The numbers within the curves indicate the pool lengths)

The correlative examination (figure 14) showed that the relationship between v and both SR and SL was positive and statistically significant at aerobic (IC_2) to maximum speeds (IC_4) in SR, and correspondingly at slow (IC_1), submaximum (IC_3) and maximum speeds (IC_4) in SL comparisons. A significant negative correlation between SR and SL existed throughout the exercise. The examination of v in connection with the phase duration showed that v was increased by reducing the time spent during the stroke cycle. This was seen particularly in catch phase which had a statistically significant negative relationship with v at AT-level and above (IC_3). Pull and push times correlated positively with v throughout the exercise.

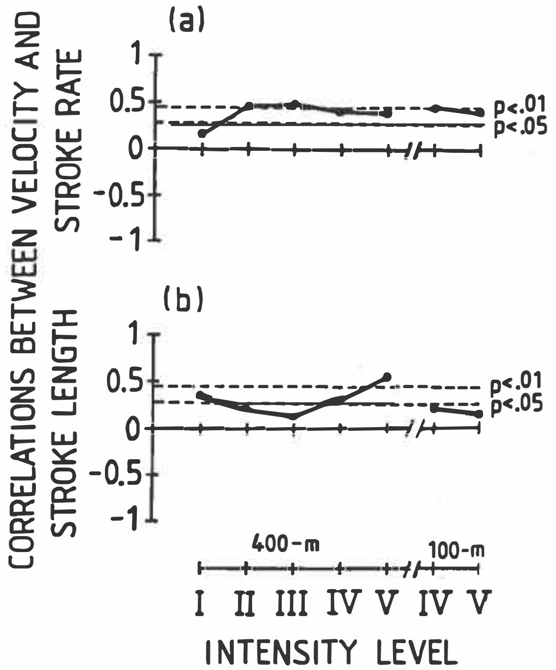

FIGURE 14 Correlation coefficients between velocity and stroke rate (14A), and between velocity and stroke length (14B) at five intensity levels in n*400-m and 2*100-m swims. Intensity levels: I=IC_1, II=IC_2, III=AT, IV=IC_3, V=IC_4.

4.5 Stroke parameters and physical conditioning

Study IV aimed to examine the effects of physical conditioning on both performance and technique variables during a fitness test. The blood lactate profiles, as described by the BLa versus v curves drawn separately for the three fitness groups (figure 15), demonstrated that the best swimmers (group I) obtained the highest, and group III (least good performers) the lowest values in v at all intensities corresponding to fixed BLa levels. The initial level in BLa at intensities below the AT were lowest in group I and highest in group III swimmers. However, no difference was found in the maximum of BLa between the groups.

Both the SL and SI showed statistically different values between the groups at all intensities. The maximum values for SL were 2.557±0.179, 2.426±0.254 and 2.293±0.128 m*cycle^{-1} in groups I, II and III, respectively (figure 16). When the point of maximum SL was reached, BLa started to increase above its initial level. However, SI reached maximum in v which corresponded to highly different BLa levels (2-11 mmol) group I swimmers demonstrating the highest and group III the lowest values (3.695+0.315, 3.339+0.286, 3.134+0.336). In SR comparisons (figure 17) the best swimmers could perform with highest V at certain SR levels as compared with their inferior counterparts.

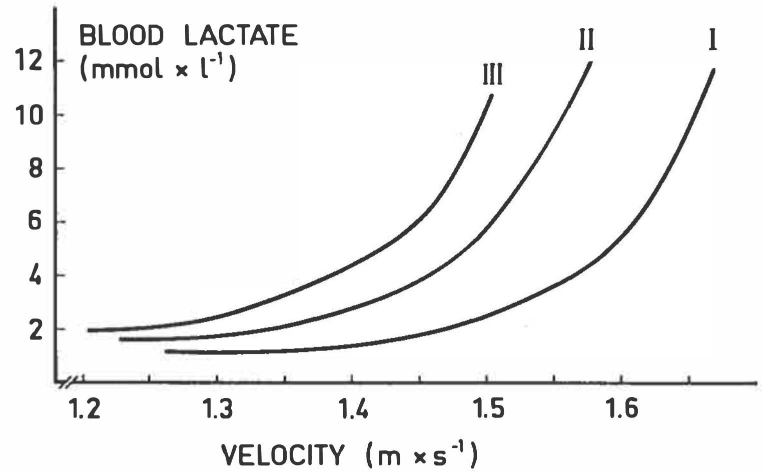

FIGURE 15 Blood lactate concentration in relation to swimming velocity in swimmers representing three fitness categories.

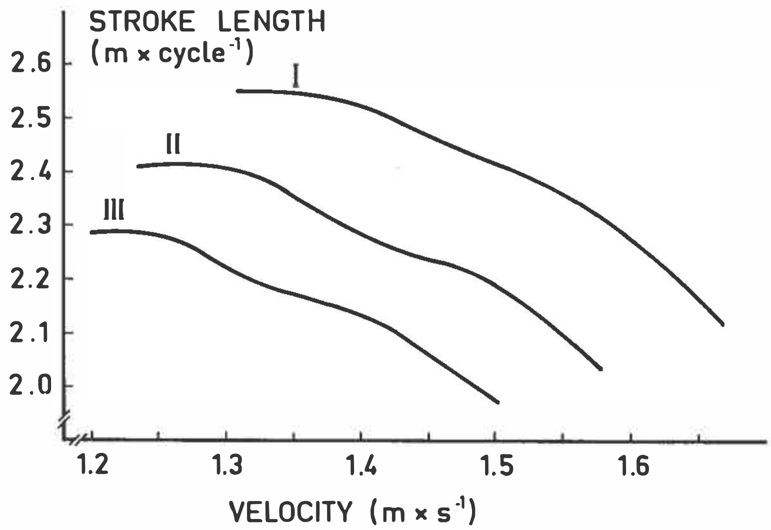

FIGURE 16 Stroke length in relation to swimming velocity in swimmers representing three fitness categories.

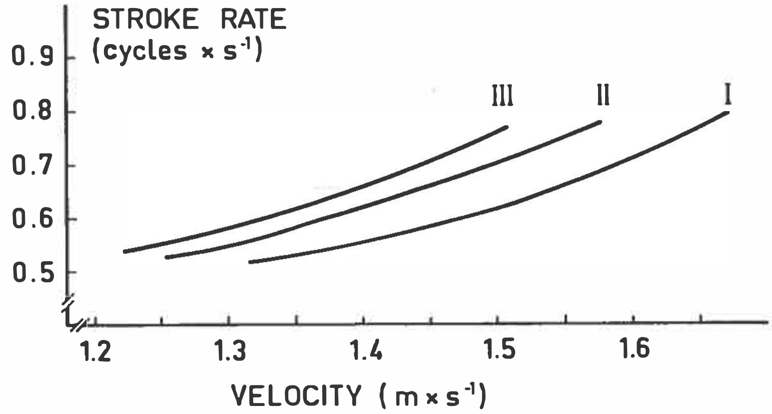

FIGURE 17 Stroke rate in relation to swimming velocity in swimmers representing three fitness categories.

Study III aimed to examine the influence of the level of force production on stroke parameters in sprint swimming conditions (IC_5) by examining the interrelationships among maximum force (MF), maximum velocity (MV), SR, SL and SI. The values for the average MV were 1.755±0.132 m*s^{-1} and 144.4±34.5 N for the average MF. Figure 18 shows the individual plots of the two variables and their high correlation (r=0.86). MV correlated positively to SL (figure 19) and SI (r=0.59 and r=0.825 respectively). The correlation coefficient between MV and SR_f was not significant. MF correlated positively to SL and SI (r=0.62 and r=0.784 respectively). As in free swimming, a non-significant correlation coefficient was noted between MF and SR_t in tethered swimming.

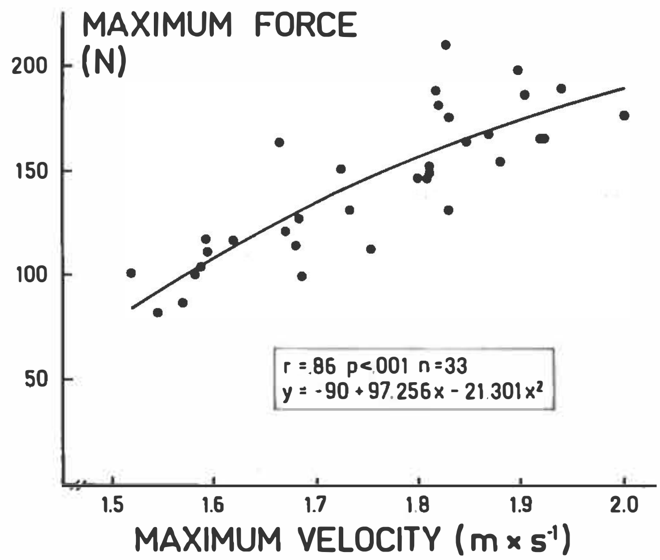

FIGURE 18 Relationship between maximum force and maximum velocity in Study III.

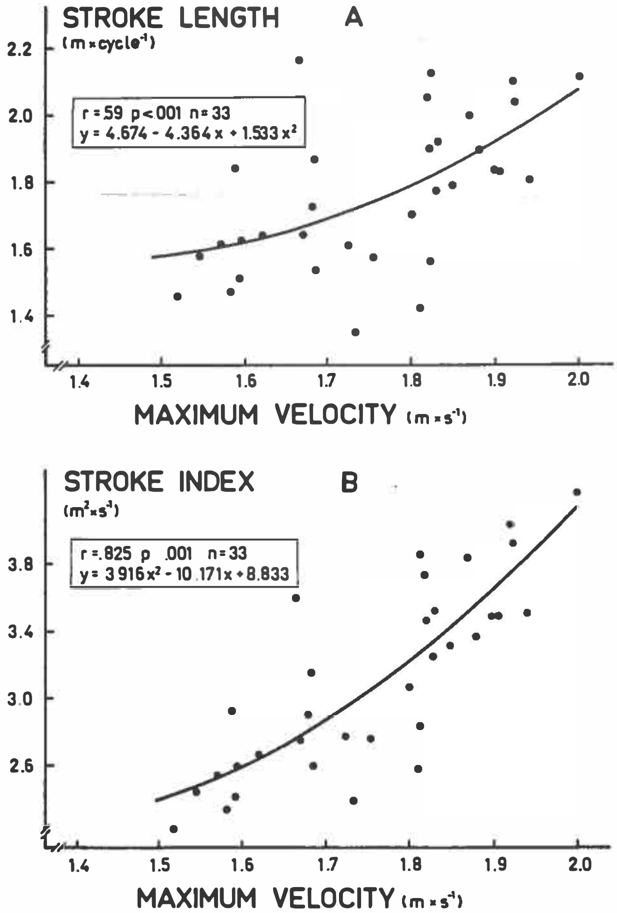

FIGURE 19 Relationships of maximum velocity with stroke length (19A) and stroke index (19B).

4.6 Stroke parameters and swimming mode

The comparison between BLa and v diagrams (figure 20) for CN and CA swims, revealed that the two curves were almost identical in low intensity until the anaerobic threshold (AT) was reached. The curves became different ($P<.05$) in v at ΔBLa corresponding to 0.5 mmol*l^{-1} increase above the initial level, and this difference stayed significant thereafter at each tested stage of ΔBLa up to the maximum effort.

The examination of BLa, v, SR and SL showed that SR and v (figure 21) were positively interrelated through all tested conditions from IC_1 to IC_4, while SL and v demonstrated a more complex relationship (see figure 8). The comparison between SL and v, as well as SL and ΔBLa (figure 22) showed that SL was longest at around the area of the aerobic/anaerobic transition (IC_2; between I- and AT-points in figures 8 and 22). The SL values were higher in the CN curve at ΔBLa level of 0.5

mmol*l-1 (I-point) above the initial level and the two curves stayed different at all v levels around the AT and above. In CA swimming SR versus v curve became different from that of the CN at higher levels of v and BLa except at the second to the last effort during the 15*100-m exercise (figure 21). However, at maximum pace the absolute SR values were equally high (0.76 Hz) in both swimming conditions. The comparison between SR and ΔBLa (figure 23) showed that the two curves became different after the Δ4 mmol*l-1 level was reached.

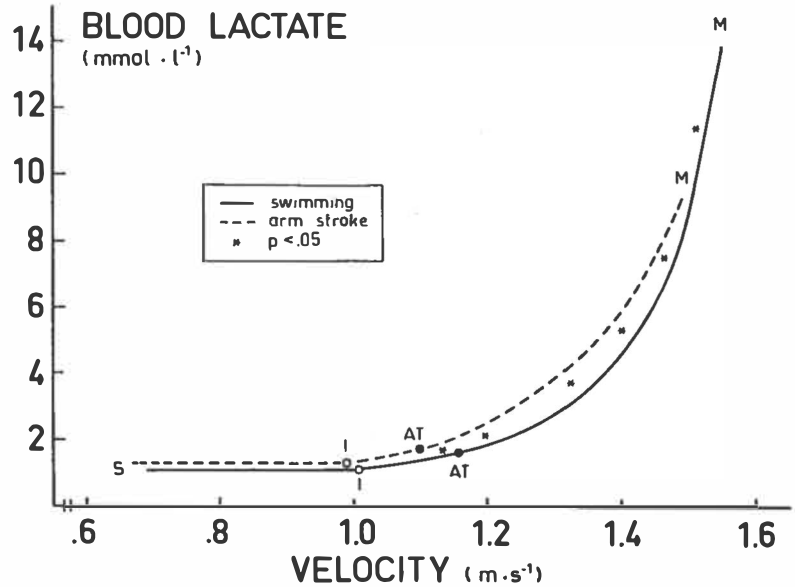

FIGURE 20 Relationship between blood lactate concentration and swimming velocity in two exercises. Symbols: S=start, I=maximum speed at initial blood lactate, AT=anaerobic threshold, M=maximum.

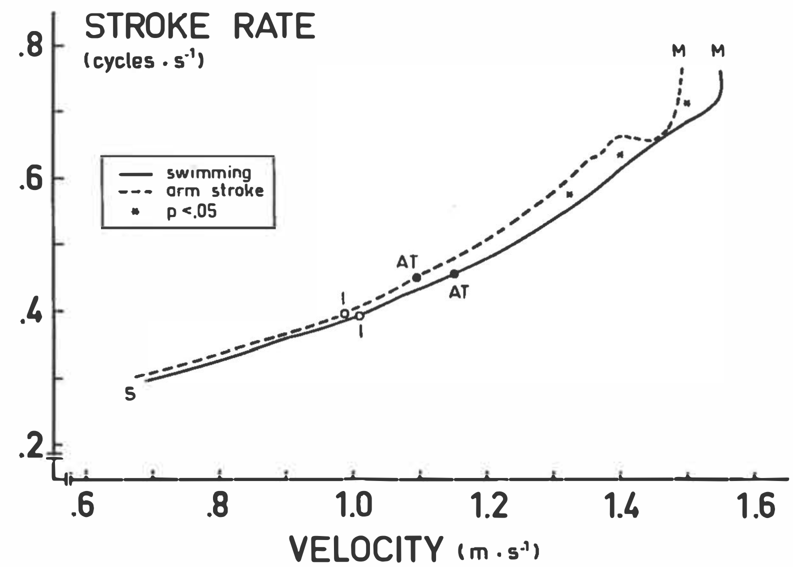

FIGURE 21 Relationship between stroke rate and swimming velocity in two exercises. Symbols: S=start, I=maximum speed at initial blood lactate, AT=anaerobic threshold, M=maximum speed.

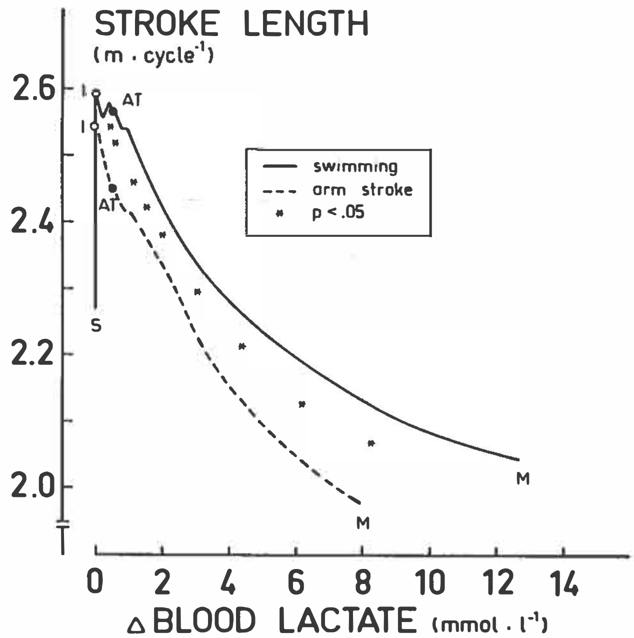

FIGURE 22 Relationship between stroke length and change in blood lactate in two exercises. Symbols: S=start, I=maximum speed at initial blood lactate, AT=anaerobic threshold, M=maximum speed.

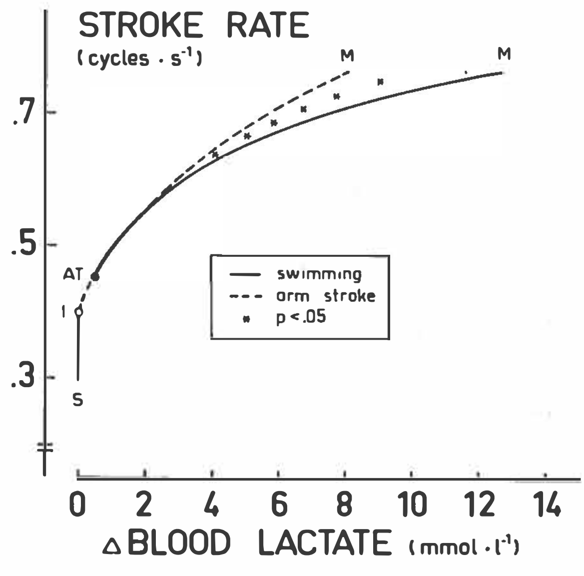

FIGURE 23 Relationship between stroke rate and change in blood lactate in two exercises. Symbols: S=start, I=maximum speed at initial blood lactate, AT=anaerobic threshold, M=maximum speed.

4.7 Stroke parameters and anthropometric variables

MV and SL were found to be positively interrelated with the anthropometric variables (H, AS, AS:H, TL, M) with the exception that the correlation between the AS:H-index and MV was statistically non-significant. On the other hand SR_f had a negative significant correlation (r=-.528) to the AS:H-index. SI, which has been used as an index of stroking efficiency and MF, which is a measure of propulsive force in stroking, correlated positively to all measured anthropometric variables. When the variables were related to age the only non-significant relationships were to SR_f and SR_t.

5 DISCUSSION

5.1 Initial stroking strategy

The findings of the present study demonstrated that the initial stroking strategy between v, SR and SL in variable training conditions, corresponded well with those in competitive situations. Thus, the most important pathway to increase v during both competition and practice, was to increase SR correspondingly. On the other hand, the observation that SL decreased with increasing v, would mean that it is a necessary incidence that SL decreases along with the increase in v and SR when the intensity level has not been specified. This is in a good agreement with previous observations made by e.g. East (1970), Satori (1975, 1976), Craig & Pendergast (1979), Letzelter & Freitag (1982, 1983), Hay & Guimares (1983), Pai & al. (1984), Craig & al. (1985). The meaning of this initial strategy between v and SR, would therefore be best described by the suggestion of Hay (1987) who stated that to increase speed in the short term, for example in a situation that requires major efforts to be employed, such as, at the finish of a race, one should strive to increase SR.

Study I demonstrated that the general interrelationships between v, SR and SL were curvilinear rather than linear. It thus means that the whole range of speed variation during the training cannot be explained by the initial strategy only. On the other hand, Study II showed that the scatter of points varied between comparisons, and it was especially large in SL versus v comparison (see figure 4), while a very close relationship and a smaller scatter of points existed between SR and v (figure 5), as well as between SR and SL (not seen in figures). These examples refer to the necessity of being able to attain high values in SR generally, in order to be able to increase v at levels which correspond to the requirements set by the competitive circumstances. However, as also e.g. Letzelter & Freitag (1982 and 1983), Hay & Guimares (1983), Craig & al. (1985), and Toussaint (1990) pointed out, the SL is one of the most important performance-determining factors. Therefore one should also pay considerable attention to resisting the reduction of SL during the course of a training session or competition.

5.2 Stroke parameters and enhanced swimming intensity

The major findings of the present study demonstrated that the values of v, SR and SL changed under the influence of progressively increasing speed during different phases of aerobic/anaerobic loading, and the five intensity categories under examination were characterised by different relationships among the stroke parameters. When the comparisons were made between the relationships within the intensity categories, it was noticed that only the IC_3 speeds, around the AT and above, were similar to the initial strategy (see figures 4, 6-8, 15-17, 20-23). This observation points out that there are different stroking strategies depending on the stage of loading. The short term strategy, which equals the initial strategy, would thus be best seen in IC_3 swims where the major changes take place also in the energy metabolism (see e.g. Mader & al., 1979).

In very slow aerobic (IC_1) swims the speed increase was produced by the increase in both SL (figure 8) and SR (figure 21) when the BLa values stayed at their initial lowest levels. The lack of major anaerobic stress and/or the ability of the acid-base buffer systems to prevent excessive changes in hydrogen ion concentrations during slow speed swims well under the AT, would allow a natural lengthening of SL free from local muscular fatigue. The slowly increasing SR would under these circumstances represent the normal short term strategy to increase v, i.e. the initial stroking strategy. However, the power of leg kicking during the course of the training sessions was not controlled. As seen in figure 8, the whole stroke swimming (CN) enabled longer SL in IC_1 swims as compared to CA swimming. Thus, it seems evident that the lengthening of SL was taken from the increased power of the legs action and, therefore, there wouldn't be any additional work done by the arms. This suggestion conforms to the observation of Hollander & al. (1988) who noticed that there was no gain in power output for arm swimming when kicking was included in sprint swimming.

During the IC_2 swimming, the SL values were maximised (see figures 4, 8 and 22) and characterised by slowly but irregularly increasing BLa. Meanwhile, it was noticed that the SR increased continuously (see figures 5, 17, 21 and 23). This phase of the exercise was located somewhere in between the pure aerobic and increasingly anaerobic paced swimming, i.e. the aerobic-anaerobic transition. The high level of SL might thus indicate that even though there was a noticeable anaerobic stress at IC_2 swims, as demonstrated by slow formation of lactate, the speed still was not fast enough to cause accumulation in BLa. But just after the AT-level was reached, the SL values began to decrease (see figures 4, 8, 11-C, 22) along with the increase in BLa. Thereafter the decrease in SL and increase in SR became more vigorous towards the end of the exercises at IC_3 and IC_4 swims. These observations suggest that the changes in the technique variables, as described especially by the SL, could be attributed to simultaneous changes in the metabolic variables, as described by the BLa. This is in a good agreement with Weiss & al. (1988) who observed that SL decreased and SR increased in a linear manner up to the AT, and thereafter with the onset of blood lactate accumulation, the stroke was shortened and consequently the swimmers required a higher SR.

However, the present data showed relatively large inter-individual variation in the exact location of the occurrence of the collapse point in SL, so that some individuals did not show marked decline in SL even at the AT. On the other hand, some swimmers did have a clear collapse in the SL curve even before the AT. These findings lead one to suspect that physical conditioning might also have something to do with the variations within the SL versus v relationship. Furthermore, Wakayoshi & al. (1992) studied a concept of critical speed, which is a speed faster, and with a considerably higher BLa than the traditional AT, but which the swimmer can yet still tolerate for a longer period of time, e.g. in competition. The SI curves reached their maximum values at speeds which might be considered the same as this critical speed. However, more research needs to be done to solve this connection.

As shown by figure 4 the collapse point in SL curves occurred at a different v in n*100-m as compared to n*300-m swims. This finding might be explained by the results of Study VI (see figures 11-13) where the early part of the swims had a very different stroking strategy as compared to those in the middle part of the swims. The 100-m swims would therefore conform to the optimum stroking strategy (see figure 12) where the fatigue cannot be seen, while the 300-m swims would correspond to a situation where fatigue progresses. The metabolic demands were found to be different between the four different modes of training as examined in the Study II (see also Keskinen & al., 1989). At the initial level of BLa, a 0.7 $mmol*l^{-1}$ difference was found between the n*300-m and n*100-m swimming sets. The cause for this difference was considered as a difference in lactate elimination rate between 100-m and 300-m distances. In higher intensity levels with increased BLa, the duration of the single swims during the sets seemed to be the primary cause of the different type of BLa behaviour in relation to v (Keskinen & al., 1989). This difference in the energy metabolism could then be seen also in the technique variables (SL, SR).

During the medium-intensity swimming (IC_3), the stroking strategy was noticed to be almost identical to the initial strategy among stroke parameters. The only exception was the lack of statistically significant negative correlation between v and SL (figure 6B). This emphasises a large range of inter-individual variability as seen in SL (figure 4). The high-intensity swimming (IC_4) differed from the low-intensity swims (IC_2) so that there was a significant correlation between v and SR (figure 6A) but no significant correlation between v and BLa, SR and BLa (figure 7B), and SL and BLa (figure 7A). This may demonstrate great variability among swimmers in swimming efficiency and in lactate production during the present type of progressive set of 100-m swims. These notions agree with Craig & al. (1985), who stated that the best performers in the 1984 USA Olympic Swimming Trials increased their SR more than a group of slower swimmers. Craig & al. also reported longer SL in the best swimmers compared to their inferior counterparts, and, more importantly, they demonstrated that the increase in competitive swimming velocities during an 8-year period from 1976 to 1984 was mainly due to increased SL (Craig & Pendergast, 1979; Craig & al., 1985).

In the 10-m maximum velocity swim (IC_5), SR, which has been found to be the determinant factor to speed increase in submaximal intensities, correlated non-significantly to MV ($r=-0.19$). On the other hand, SL, which, has been found to be negatively related to v in medium intensities, correlated positively to MV ($r=.59$; $p<.001$). Craig & Pendergast (1979) demonstrated that during an incremental series of 22-m swims the increase in SR produced an increase in v. At very high swimming velocities after the maximum level of SR was reached, no further increase in v occurred. In fact the v decreased with excessively high SR. In the present data, the SR_f was obtained in natural free swimming conditions and these values can therefore be considered to correspond to the optimum value of SR (Craig & Pendergast, 1979). It is thus suggested that in maximum swimming conditions the relationships between v, SR and SL reflect the ability of a swimmer to swim with high efficiency. This means the effective use of stroke technique, as expressed by SL, and consequently with high levels in propulsive force.

Similarly, this means that no excessive frequency can be used while stroking. The findings of Craig & al. (1985) agree with these suggestions. They noted that over an eight year period the increase in competitive swimming performance of international top swimmers was caused mainly by the increase in SL, whereas in most of the events SR had decreased. In the present maximum v swims the inter-correlations were similar to the earlier findings of Study I in low intensity swimming. One might assume that the training in low intensity paces, by emphasising a long SL versus low SR, would have a parallel effect on these parameters in very high intensity swimming. The critical point, however, is the performance level, and especially the ability of a swimmer to swim at MV with correspondingly long SL. Costill & al. (1985) have used SI as an index of the stroking efficiency and swimming economy. In the present data the correlation coefficients of SI were positive with MV and SL. Although the relationships of SI and SL to MV were nearly identical, and although the relationship between SI and SL was highly linear (r=.941), it is suggested that either SL or SI could be used as an index of the stroking efficiency in this kind of situation. It must be noted that SI, especially, is technical, since it includes both MV and SL, and therefore the meaning of SI as an individual parameter might be questionable.

When a selected intensity level is used as a training mode the relationships between the variables do not necessarily conform to the initial stroking strategy. The present results suggested that during low-intensity (IC_2) training it is beneficial to practice the lengthening of SL, in order to develop local muscular endurance. In medium-intensity (IC_3) swimming, even when there is the necessary tendency to increase SR, it is important to try to resist the decrease in SL, in order to develop greater muscular power output and mechanical swimming economy.

Satori (1975) reported that the German observation group found many top swimmers, especially in the DDR team in XIIIth European Swimming Championships in Vienna 1974, concentrate on SR adaptation in their warm-up protocols instead of measuring time for lap as has been conventionally done. This training method could be applied to the present findings, which demonstrated that the SL reached the highest values at IC_2 swimming. The tempo training would under these conditions help to increase the economy, and also mean that the swimmers would train by using the SR corresponding to v at AT levels. And simultaneously they would try to maintain the level of SL values at a constant high levels, or even try to manage with one or two strokes less than before, without losing their control on SR.

Cecil Colwin (1992) wrote that 1928 Louis B. de Handley, observed that *"a swift stroke is not conducive to fast swimming and that, though contestants were inclined to think wild action necessary to attain great speed, this is not the case"*. Handley added that slow arm movements with a vigorous drive and a restful recovery give the best results. Jack Nelson (1973) introduced the concept of DPS (distance per stroke) and his swimmers practised drills designed to increase SL. Colwin writes that, basically, these drills enable a swimmer to improve efficiency by feeling what one arm does by itself. Nelson also developed an exercise in which the swimmer repeats 100-m swims keeping a 24 stroke count for each 100 m. Swimmers who cannot maintain this rating are allowed to do a set number of strokes more suited to their individual ability. Ron Johnson (1982) introduced the "Tempo Awareness Training" at the World Clinic of ASCA. He mentioned that he had seen the Hawaiian coach, Soichi Sakamoto, counting tempo to his swimmers as far back as the 1941 American Championships. Johnson maintained that, whereas there had been much emphasis on reducing the number of strokes per length, there had been little development of what he termed "tempo awareness". Johnson was convinced that only two factors made a real difference to swimming speed, and they were distance per stroke and stroke speed. Johnson outlined methods for measuring tempo as the time taken to complete 2, 5 or even 10 arm cycles. Johnson also introduced methods for timing stroke tempo with a 1/100-second stopwatch or a computer. For freestyle, Johnson said that a typical tempo for a middle-distance collegiate swimmer is around 0.74-0.77 Hz. For a good college male sprinter a typical tempo is around 1.05 Hz, and females at elite level approximately 0.05 Hz faster than men.

Costill & al. (1985) also pointed out the importance of swimming with the fewest number of stroke cycles at a given velocity. In high intensity swimming v may be increased by increasing the SR. Furthermore, if the suggestion is true that an optimal level of SR during competitive swimming exists (e.g. East, 1970; Hay, 1978; Craig & Pendergast, 1979) then the swimmer should use this "optimum" SR in his/her training. At low- and medium-intensity training, the lower SR with longer SL may be desirable. These suggestions point out that the interrelationships between SR and SL should urgently be considered in the training of swimmers.

5.3 Stroke parameters and swimming distance

The results from Study II demonstrated considerable effects of swimming distance on stroke performance, and especially on SL under the influence of enhancing swimming intensity (see figures 4 and 10). When the comparisons were made between the maximum performances of different swimming distances during the exercises, it was shown that the shortest (10-100 m) distances were performed with significantly higher values in v and SR and lower values in SL and SI than the 300- and 400-m events. These observations thus conformed well with the earlier observations made in major swimming competitions world wide (East, 1970; Satori, 1974-1980; Craig & Pendergast, 1979; Hay & Guimares, 1983; Craig & al., 1985; Wakayoshi, 1988; Nelson & al., 1990; Chengalur & Brown, 1992; Kennedy & al., 1992; Wakayoshi & al., 1992).

However, when the comparisons were made at IC_2 level, it was shown that there was no statistically significant difference between the absolute maximum values of SL in 100-m and 300-m distances at around the aerobic-anaerobic transition (see figure 4). However, the point of maximum SL was found at different v. This observation might lead one to assume that there would be a certain standard level of SL for each individual when the swimming is free from major anaerobic stress in lower intensity swims. In the present situation it was below the AT. This standard SL would, however, be found at speeds corresponding to differences between the individuals, due to the intensity level during a training session, due to swimming distance, and yet still due to factors related to an individual's physical characteristics and technical ability itself.

Study VI introduced very interesting results concerning the stroking strategies between v, SR and SL. As shown by the figures 11, 12 and 13, the relationships of both SR and SL in relation to v, demonstrated that during the early part of each swim, especially during the first laps, and independent from the swimming distance, the stroking followed a different strategy than during the following pool lengths. These first lap curves, for both SL versus v, and SR versus v relationship, could then be used to estimate the progression of fatigue of a swimmer for each swimming distance separately. On the other hand, the development of endurance in technique performances could also be followed with the help of these first lap curves in comparison with a given distance, longer than 50 m. Furthermore, the optimum curve for a short distance could also be constructed by utilising the protocol similar to what has earlier been described by Craig & Pendergast (1979).

It is suggested that the observed differences in stroke performances between the swimming distances under examination, could be explained by three different ways. Firstly, the primary goal to obtain high levels in v in general, is to increase SR to relatively high levels, which level in turn is dependent upon the distance performed. Secondly, each distance seems to allow a certain level of SL and SR which, however, are individually rather than generally arranged. And finally, the third reason to the observed differences in stroke performances between the swimming distances, is due to a swimmer's personal ability to produce and endure highest possible values in SL and, consequently, to be able to compete successfully in each specific distance separately.

5.4 Stroke parameters and successive pool lengths

The results of the Study VI showed that the initial stroking strategy during the test exercises (n*400 m) was not very much different from that observed in competition. Thus, the interrelationship between v and SR was positive and the performance level was greatly affected by the values of SL. In addition, the early part of the 400-m swims was different from the remaining seven laps (see figures 11-13). This is similar to the observations in competitive situations. For example, the data reported by Letzelter & Freitag (1982 and 1983) suggested that the difference in curve patterns between the first and consecutive laps was caused by the additional high velocity due to the start from the starting block. In the present study the situation was different because the subjects started to swim from the water. Thus there was no gain in v from any other sources than those related to swimmers' physiques or techniques. The most evident explanation would be the 2-min rest period between the 400-m swims. According to the findings of Hultman & al. (1967) the major portion of the adenosine triphosphate (ATP) and creatine phosphate (CP) used during training would be restored to the muscles within 2 min, and ATP and CP would be completely restored in 3 min. is therefore hypothesised that in the present situation, these stores could be used again during the early part of the subsequent 400-m swims and observed especially from the first lap curves in comparison with the seven other ones.

The initial stroking strategy between the discussed parameters include the decrease of SL with increasing v. The first lap curves of the five to six 400-m swims (figures 12 and 13) complemented with the plots of the 100-m swims, correspond to this strategy. The first lap curves may therefore be considered as the optimum curve. Thus the deviation of the curves for laps 2-8 from that of the optimum, would imply the progression of fatigue during the swims. On the other hand, the swimmers were instructed to pace their swims evenly by looking at the pace clocks placed along the pool side. If they started swimming at a different speed than was the predetermined target, then they were instructed to continue with this newly selected speed. is therefore suggested that it is not only a question of the physical potential of a swimmer to swim with a correct pacing but also a question of skill or ability to use one's subjective perception to produce a certain speed. Unfortunately the present data could not provide evidence enough to state whether the reduction in the measured variables during the early part of the swims was due to real physiological fatigue or due to the subjects' skill in keeping the swimming speed steady throughout the 400-m swims.

As seen in figure 11A-C, the curves for v, SR and SL during the 400-m swims changed in relation to increase in swimming intensity. When the speed was slow or aerobic (low BLa) the swimmers could control their velocities and simultaneously keep the SL values at their constant high levels throughout the 400-m swims. However, when the intensity increased over the anaerobic threshold level, the reduction in SL became progressively greater. This may be explained by the developing local muscular fatigue. The findings of Studies I and II as well as Weiss & al. (1988) support this suggestion, and when combined with the results of Study VI, may imply that the increase in blood lactate concentration may change the stroking strategy significantly. When the velocity increased up to the submaximum and maximum levels (high BLa), the swimmers of Study VI tried to maintain their speeds by increasing SR and at the same time by trying to resist the shortening of SL. The reduction of SL above AT would therefore be connected to the accumulation of blood lactate, while SR would primarily be determined by the ability to maintain adequate neural activation.

The common solutions to technique testing involve taking samples of a technique performed by a physiologically fresh swimmer. The results of the present Study VI demonstrated that these samples may not correspond to a technique recorded in a situation with a longer duration. It is therefore suggested that in order for the technique testing to be more beneficial, unfatigued swimming should be compared with competitive swimming, where fatigue progresses.

5.5 Stroke parameters and physical conditioning

The results of study IV demonstrated the well-known effects of endurance training on physical fitness, as seen in figure 15. The BLa versus v curves indicated that the best performers could maintain the BLa values at the lowest initial levels with significantly higher values in v than their inferior counterparts. On the other hand, the results also showed that the physiological responses could be attributed to the values of technique performance, as shown by the SL (figure 16), SR (figure 17) and SI (not seen in the figures) in relation to v. One might thus suggest that these variables could be applied to describe the effectiveness of swimming technique during the course of the present type of physiological testing (see also Keskinen & Komi, 1989).

Furthermore, the finding that v at maximum SL is close to the same as the so-called anaerobic threshold according to the BLa versus v curves (see also Weiss & al., 1988) suggest, that during an incremental loading the accumulation of blood lactate leads to parallel development of local muscular fatigue as shown by the decrease in SL. While the observed changes in SL were similar in all of the examined groups, the lengthening of SL throughout the intensity categories and especially around the AT, in addition to the simultaneous reduction in SR, could be considered as positive effects of endurance training on biomechanical performance in swimmers. The finding that the v of maximum SI corresponded to highly different BLa levels might lead one to suggest that the different specialisation of the swimmers between sprint and distance events might be demonstrated by the SI concept. As a consequence of that, the finding that the v observed at maximum SI would be close to the same as the so-called critical speed (Wakayoshi & al., 1992), would lead one to suspect that the physical conditioning would also have something to do with the concept of maximum SI. However, the present data could not provide further evidence of that connection.

Several studies demonstrate that the muscular force of a swimmer influences swimming performance especially in sprint distances (Miyashita & Kanehisa, 1979; Adams & al., 1983/1984; Costill & al., 1983). The forces exerted during continuous swimming are far from the peak forces which the swimmer is able to produce during dry land exercises or even during tethered swimming (e.g. Yeater & al., 1981). The data from study III demonstrated positive non-linear interrelationships between MV, MF and SL (see figures 18-19 and 9). These findings suggest that the effective stroke technique, which is fundamental to MV, could be regarded as the result of longest possible SL (figure 9) while the force production values remain below the true maximum. When the force production is measured during tethered swimming, the full capacity of the propulsive segments of the body can be used. Nevertheless, the force values decrease with the increase in swimming velocity, as was noted by Alley (1952). The possible explanation for this could be that at very high speeds it is not easy to produce very high force values and the force-velocity relationship of the skeletal muscle (Wilkie, 1952; Komi, 1973) must be considered in this context.

5.6 Stroke parameters and swimming mode

The present data from study V, demonstrated the considerable effect of leg action especially by SL comparisons (figure 8). At around the AT level, the difference in SL was about 11 cm (4.5 %) in favour of CN and even larger at v above AT. Although the difference was nearly the same between CN and CA in low pace swims (IC_1), it was not statistically significant. This may be partly due to a large variation in individual SL values in this phase of the training session. It seems evident that CA was a very economical way of swimming just before the increase in BLa started. But after the AT was reached the lack of support from the legs could be seen from the lowered SL values as compared to the CN swimming. These findings agree with those of e.g. Holmer (1974b) who noticed that CA swimming demanded lower VO_2 at a given submaximum v than the CN swimming, but at maximum speeds the whole stroke swimming was superior to the CA swimming in both oxygen consumption and performance.

However, SR was very similar between the two different 15*100-m sets at v less than 1.3 $m*s^{-1}$ (figures 21 and 23). This suggests that SR and v were strongly interrelated at submaximum intensity levels (IC_3), while SL depended also on such factors as muscle force of the upper extremities as seen in figure 9, and on the support of the leg action during swimming, as demonstrated by figure 8. Hollander & al. (1988) observed that at maximal speed in sprint swimming, the effective power of leg kicking was 14.6 W and 127 W when using the arms only, whereas the output of the arms during swimming the whole stroke was 123 W. This means that there was no gain in power output for arm swimming when the leg kicking was included. However Hollander & al. (1988) registered higher v in the whole stroke swims compared to CA swims. As seen in figure 21, the CN and CA swims were performed with similar maximum values in SR. When this result is connected with that of Hollander & al. (1988), one might suggest that the additional high velocity in CN compared to CA swimming, in both studies, was caused by the increase in SL as a result of leg kicking in CN swimming. This suggestion gets support from Watkins and Gordon (1983) who concluded that the leg action contributes indirectly to propulsion by stabilising and streamlining the body at full speed.

An interesting observation can be made from figure 21 where the CA curve became nearly identical to the CN curve at v of 1.46 $m*s^{-1}$. It occurred in almost every subject during the second or third to the last effort. This may be a result of a dolphin kick when the subjects were trying really hard. The very last effort was then so exhaustive that the CA curve again became different in v from that of CN. This observation indicates the necessity of being able to use one's full potential to obtain maximum performance. It is thus suggested that if one wants to improve swimming economy at submaximum intensities, CA swimming should be practised at around the aerobic-anaerobic transition with high SL and low SR concept. Under these conditions kicking would be compensated by pull-buoys to keep the body in a streamlined position. However, the high intensity exercises at race pace or near the absolute maximum, should include the leg kicking in order to obtain the best possible adaptation to competitive requirements in terms of competition-like co-ordination between upper and lower extremities.

5.7 Stroke parameters and anthropometric variables

The anthropometric variables measured in study III were selected according to the previous findings of e.g. Toussaint & al. (1983) and Grimston & Hay (1986). These papers observed that arm length, leg length, and hand and foot size were significantly related to swimming performance, SL and SR. In the present data the arm span (AS) including the length of hands, forearms, upper arms and shoulders was used to describe the main propulsive part of the body. The standing height (H) and the total length of the body with the extremities extended (TL) were used to describe the whole body size of a swimmer. These variables were shown to correlate positively with MV, SL and MF. Although body size is positively related to swimming performance, the most important anthropometric factor is the surface area of the upper extremities and AS. Also the results of Toussaint & al. (1991) indicate that with an artificially enlarged propelling surface area (hand paddles) the same velocity can be maintained with a decrease in the rate of energy expenditure. Thus it is essential for a swimmer to have a large AS and the ability to use it effectively. It therefore seems possible that if AS is very long but the swimmer is incapable of reaching high velocities during swimming, this is due to either lack of muscle force or skill. This is especially relevant to young swimmers who have reached their final standing height but not yet gained full muscular strength. Thus the physical growth and regular training results in more effective use of the propulsive components of the body leading to both higher v and longer SL values in high speed swims. The AS:H index has been used to describe the overall linearity between the AS of the upper extremities and the H of a swimmer. In the present study the AS:H-index correlated positively to MF and SL but negatively to SR. This leads one to expect that the swimmers who posses very high values in both AS and the AS:H -index should try to increase their muscular strength in order to produce high SR combined with relatively long SL, which could thereafter increase the level of their performance in the water.

Nevertheless, the force-velocity relationship sets a general limit for force to increase v. There is documented evidence, however, that proper training could also be applied to increase high shortening velocities in muscle (e.g. Häkkinen & Komi, 1985; Häkkinen & al., 1985). Also, the great variance observed in MF values suggests that proper specialised strength and power training could be applied to swimming. Finally, the observed interrelationships warrant the suggestion that there should be an optimum balance between the anthropometric growth and force development in order to optimise the stroke performance in attaining a high MV.

6 CONCLUSIONS AND SUGGESTIONS

6.1 Conclusions

The present study sought to find answers to questions which are related to some of the fundamental problems among swimmers and coaches: *Why are the techniques of swimmers so variable during both competition and practice?; Why are their technical performances continually changing during practice?; Is it possible to measure technique performances in order to follow their development in swimming skills?* To examine these questions, seven more specialised questions were listed.

The major findings showed that the variability of the techniques could be attributed to several factors related to at least three different elements which could be considered as the determinant factors of the technique performances during exercise: (1) the initial stroking strategy between the parameters fully responsible for the stroke performance during swimming in the short term, (2) the factors modifying the initial strategy in both short and long term, and (3) the individual factors determining the stroke performances during swimming, especially in the long term.

The initial stroking strategy among the stroke parameters demonstrated that the increase in v was associated with the increase in SR, and the decrease in SL. Thus the main pathway, in situations requiring major efforts to be employed to increase speed in the short term, for example at the finish of a race, would be that the swimmer should strive to increase SR and simultaneously try to maintain a steady SL or at least try to resist its necessary shortening. However, the relationships were curvilinear rather than linear, and this therefore leads one to assume that the whole range of speed variation during the exercises cannot be explained by the initial strategy only.

The major factor to modify the stroke performance was swimming intensity as such, especially in relation to the lactacid anaerobic energy metabolism. SR followed the initial strategy and did not seem to be much affected by the enhanced intensity levels other than was necessary to increase the speed in general. Therefore, the positive relationship between SR and v stayed significant throughout the studied intensity levels except at very low and maximum alactacid sprint speeds. On the other hand, the SL responded very sensitively to speed changes. Especially as described by the effects of the enhanced swimming intensity, variation in the distance to be swum, swimming mode, and the variation within the entire swims. It also seemed evident that fatigue, developed during the exercises and observed from the changes taken place in the physiological parameters, could also be attributed to parallel changes in the SL values. The behaviour of the SL during exercises could be described by the parameters connected to the status of the individual's physical conditioning, force production capacity in the water, and anthropometric characteristics.

As for an answer to the third fundamental problem - *is it possible to measure technique performances in order to follow the development of the swimmers in swimming skills?* - this study concludes that the observed changes in swimming technique and the close connection of the technique parameters with the corresponding changes in the physiological variables gives a clear basis for technique testing. Thus, it is suggested that the measurement of technique variables, under the influence of physiological stress and simultaneously with physiological parameters, should be used to measure the effects of training in swimmers. This can be done by examining the relationships between v, SR and SL in standardised pool testing conditions,

6.2 Suggestions for further developments in testing

Based on the findings of the present study, it was concluded that swimming technique, although highly variable, can be examined to follow the conditioning effects of swimming training. The standardised pool testing protocols, when complemented with procedures described by the present data, can be used to analyse both the physiological and biomechanical responses of swimming training in the same testing session.

The methods standardised especially for pool testing conditions (Mader & al., 1976; Gullstrand & Holmer, 1980; Simon & al., 1982), and commonly used to estimate the physical conditioning of the athletes in aquatic sports, have been shown to be valid for this kind of testing purposes. As the differences in the test results are known (Keskinen & al., 1989), and when these differences are taken into consideration when applying the results to practice, there would not be any problems in utilising each of those tests in the control of the training process. In addition, the distances of 200 and 400 m have increased popularity in testing of swimmers with rather similar protocols, as reported by Gullstrand & Holmer (1980) and Simon & al. (1982). Furthermore, in order to be able to distinguish between the changes observable only at around the aerobic-anaerobic transition phase and AT, the incremental type of protocols should be employed, if one really wants also to utilise the information derived from the biomechanical parameters. However, whatever the choice, the most important thing is that each swimmer should be tested with the same test mode in successive examinations in order to be able to make comparisons between the series of observations and to be able to utilise the collected information exclusively during the training process.

The parameters to estimate the technique performances during the fitness testing of swimmers should include the measurement of v, SR and SL separately in each of the pool lengths. The start from the starting block should not be included in order to avoid the additional high velocity in the early part of the swims. Time taken for each distance to be swum and for each successive pool length separately should be used to calculate the mean v ($m*s^{-1}$) for both the whole distance and the laps. The SR can be obtained reliably by measuring time for ten one-arm stroke cycles per lap in 50-m pools and for five stroke cycles per lap in 25-m pools without an inclusion of a turn during the measurement. The SR can then be calculated by dividing 10 or 5 strokes by the time spent to complete those one arm stroke cycles. SR should be expressed in Hz ($cycles*s^{-1}$) in order to be able the calculate SL ($m*cycle^{-1}$): by dividing v by SR.

The data should be presented in an easily understandable form so that both the technique (SR, SL) and physiological parameters would be related to v simultaneously (see fig. 2 and 3). The AT should be defined by using the definitions reported within the standardised testing procedures. The feedback to the swimmers and coaches should include a clear prescription about the intensity levels recommended for training in terms of both v and time to finalise a given distance, usually 100 m. In order for the swimmer to be able to fully utilise the information given by SR and SL, the amount of one-arm stroke cycles per lap (25/50 m) should be calculated for tempo training corresponding to the SR values, as well as for training with fixed-amount-of-stroke-cycles-per-lap procedure corresponding to the values of SL at different stages of exercises, e.g. at AT. Furthermore, the AT would be best described by an approximate area in the speed axis rather than a fixed v value, and the values for BLa, heart rate (HR) and VO_2 (if measured), as well as for SR and SL should be expressed similarly. According to the findings of Study VI, one should also consider if the first and final lap values for SR and SL are relevant to be used for tempo and fixed-amount-of-strokes training. At least one or two stroke cycles should be added to these numbers (100-m tests), or the values measured in the middle part of the swims (200-, 300- and 400-m tests) should be used when programming the endurance training session.

Finally, it is concluded that the measurement of technique variables, under the influence of physiological stress, and simultaneously with the physiological parameters, should be a part of the control of training in swimmers. This can be done by examining the relationships between v, SR and SL in standardised pool testing conditions.

7 YHTEENVETO

Tutkimuksen tarkoituksena oli etsiä selityksiä uintitekniikassa niin kilpailusuoritusten kuin harjoittelunkin yhteydessä havaittaville suurille vaihteluille. Tutkimus pyrki myös kehittämään käytännöllisiä tapoja mitata uintitekniikan kehittymistä säännöllisen harjoittelun seurauksena. Erityisesti pyrittiin tarkastelemaan uintiharjoittelun tehokkuudessa tapahtuvien muutosten vaikutusta krooliuinnin liikeaskelominaisuuksiin ja niiden välisiin riippuvuussuhteisiin. Tutkimuksen kohteena olleet liikeaskelominaisuudet käsittivät uinnin keskinopeuden (v, mean velocity) lisäksi keskimääräisen liikeaskelpituuden (SL, stroke length), liikeaskeltiheyden (SR, stroke rate) ja uinnin keskinopeuden ja liikeaskelpituuden avulla lasketun liikeaskelindeksin (SI, stroke index) sekä liikeaskeleen eri vaiheita kuvaavat aikamuuttujat. Uinnin tehoalueet määritettiin veren maitohappopitoisuuden ja uinnin keskinopeuden välisen riippuvuuden avulla. Koehenkilöt (87) olivat hyvin harjoitelleita mieskilpauimareita, jakaantuen viiteen eri tutkimusaineistoon.

Tutkimustulokset osoittivat että harjoituksenaikaiset riippuvuussuhteet eri liikeaskelominaisuuksien välillä olivat pitkälti yhteneviä kilpailusuorituksista kirjallisuudessa aiemmin raportoitujen havaintojen kanssa. Tämän pohjalta päädyttiin yleiseen toteamukseen, että uintinopeutta lisätään harjoittelun tai kilpailusuorituksen aikana pääsääntöisesti liikeaskeltiheyttä kasvattamalla ja pyrkimällä samanaikaisesti estämään liikeaskelpituuden lyheneminen väsymyksen aiheuttamasta päinvastaisesta paineesta huolimatta. Kun tarkastelun perusteeksi otettiin uinnin tehoalueet ja niiden sisäiset ja niiden välillä tapahtuneet muutokset liikeaskelominaisuuksissa, havaittiin, että uimarin käyttämä tekniikka muuttui samanaikaisesti fysiologisissa mittareissa havaittujen muutosten kanssa. Tärkeänä löydöksenä voidaan pitää sitä, että liikeaskeleeseen kulunut aika saavutti suurimman arvonsa silloin kun uinnin teho harjoituksen kestäessä nostettiin elimistön energiantuottoketjun aerobis-anaerobiselle siirtymäalueelle. Kun uinnin nopeutta tästä edelleen lisättiin, todettiin liikeaskelpituuden alkavan lyhentyä ja lyhenemisen olevan sitä voimakkaampaa mitä korkeammaksi veren maitohappopitoisuudet kohosivat. Tärkeimpänä havaintona voitaneen kuitenkin pitää sitä, että uintitekniikkaa kuvaavien muuttujien avulla voitiin seurata myös fysiologisilla mittareilla havaittavia muutoksia uimarin suorituskyvyssä. Tutkimustulosten pohjalta suositellaankin, että tässä tutkimuksessa käytettyjä uinnin tekniikkaa kuvaavia liikeaskelmuuttujia käytettäisiin jatkossa fysiologisten mittareiden kanssa samanaikaisesti uimarien kunto- ja tekniikka-ominaisuuksien seurannassa. Tällöin nyt lähinnä vain fysiologisia muuttujia hyödyntävät standardoidut uintitestit muuttuisivat entistä monipuolisemmiksi ja uintivalmennusta entistä paremmin palveleviksi apuvälineiksi.

8 REFERENCES

Adams, T. A. II, Martin, B. C., Yeater, R. A. & Gilson, K. A. 1983/1984. Tethered force and velocity relationships. Swimming Technique 20 (3), 21-26.

Adrian, M. J., Singh, M. & Karpovic, P. V. 1966. Energy cost of leg kick, arm stroke, and whole crawl stroke. Journal of Applied Physiology 21, 1763-1766.

Alexander, R. McN. 1975. The chordates. Cambridge University Press, London.

Alexander, R. McN. & Goldspink, G. 1977. Mechanics and Energetics of animal locomotion. Chapman & Hall, London.

Alley, L. E. 1952. An analysis of water resistance and propulsion in swimming the crawl stroke. Research Quarterly 23, 257-270.

Bailey, S. P. & Messier, S. P. 1991. Variations in Stride length and running economy in male novice runners subsequent to a seven week training program. International Journal of Sports Medicine 3 (12), 299-304.

Bailey, S. P. & Pate, R. R. 1991. Feasibility of Improving running Economy. Sports Medicine 12 (4), 228-236.

Bainbridge, R. 1958. The speed of swimming of fish as related to size and the frequency and amplitude of the tail beat. Journal of Experimental Biology 35, 109-133.

Bainbridge, R. 1960. Speed and stamina in three fish. Journal of Experimental Biology 37, 129-153.

Bainbridge, R. 1962. Training, speed and stamina in trout. Journal of Experimental Biology 39, 537-555.

Ballreich, R. & Gabel, H. 1975. Einfluss der Schrittlänge und Schrittfrequenz auf die Laufzeit in Sprintdisziplinen [Effect of stride length and stride frequency on running time in sprint distances]. Leistungssport 5, 5.

Baumann, W. 1992. Perspectives in methodology in Biomechanics of sports. In R. Rodano, G. Ferrano & G. Santabrogio (eds.), Proceedings of the 10th ISBS Symposium in Milano, 97-107.

Böhringer Mannheim: Test-Fibel 1979. Enzymatische Bestimmung von Lactat im Plasma, Blut und Liquor [Enzymatic determination of lactate in plasma, blood and fluids]. Mannheim.

Bucher, W. 1974. The Influence of the leg kick and the arm stroke on the total speed during the crawl stroke. In J. P. Clarys & L. Lewillie (eds.), Swimming II. University Park Press, Baltimore, 180-187.

Cavanagh, P. & Williams, K. 1982. The effect of stride length variation on oxygen uptake during distance running. Medicine and Science in Sports and Exercise 14, 30-35.

Chengalur, S. N. & Brown, P. L. 1992. An analysis of male and female Olympic swimmers in the 200-meter events. Canadian Journal of Sport Sciences 17 (2), 104-109.

Clarys, J. P., Jiskoot, J., Rijken, H. & Brouwer, P. J. 1974. Total resistance in water and its relation to body form. In R. C. Nelson & R. C. Morehouse (eds.), Biomechanics IV. University Park Press, Baltimore, 187-196.

Colwin, C. M. 1992. Swimming into the 21st Century. Leisure Press, Champaign, Illinois.

Costill, D. L., King, D. L., Holdron, A. & Hargreaves, M. 1983. Sprint speed versus swimming power. Swimming Technique 20 (1), 20--22.

Costill, D. L., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R. & King, D. L. 1985. Energy expenditure during front crawl swimming: Predicting success in middle-distance events. International Journal of Sports Medicine 6, 266-270.

Counsilman, J. E. 1986. Competitive Swimming Manual for Coaches and Swimmers. Pelham Books, London, 159-160.

Craig, A. B. Jr. & Pendergast, D. R. 1979. Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. Medicine and Science in Sports 11 (3), 278-283.

Craig, A. B., Boomer, W. L. & Gibbons, J. F. 1979. Use of stroke rate, distance per stroke and velocity relationships during training for competitive swimming. In J. Terauds & E. W. Bedingfield (eds.), Swimming III. Baltimore, University Park Press, 265-274.

Craig, A. B. Jr., Skehan, P. L., Pawelczyk, J. A. & Boomer, W. L. 1985. Velocity, stroke rate and distance per stroke during elite swimming competition. Medicine and Science in Sports and Exercise 17,

625-634.
Craig, A. B. 1986. Breath holding during turn in competitive swimming. Medicine and Science in Sports and Exercise 18, 402-407.
DeGaray, A., Levine, L. & Carter, L. J. 1974. Genetic and anthropological studies of Olympic athletes. Academic Press, New York.
Dillman, C. J. 1979. Biomechanical evaluations of cross-country skiing techniques. Journal of United States Ski Coaches Association 2 (3), 38-42, 48.
Durnin, J. & Rahaman, M. 1967. The assessment of the amount of fat in the human body from the measurement of skin fold thickness. British Journal of Nutrition 21, 681-689.
East, D. J. 1970. Swimming: An Analysis of stroke frequency, stroke length and performance. New Zealand Journal of Health, Physical Education and Recreation 3, 16-27.
Elliott, B. C. & Blanksby, B. A. 1976. A cinematographical analysis of over-ground and treadmill running by males and females. Medicine and Science in Sports 8, 84-87
Frischberg, B. A. 1983. An Analysis of overground and treadmill sprinting. Medicine and Science in Sports and Exercise 15, 478-485.
Gergley, T. J., McArdle, W. D., DeJesus, P., Toner, M. M., Jacobovitz, S. & Spina, R. J. 1984. Specificity of arm training on aerobic power during swimming and running. Medicine and Science in Sports and Exercise 16, 349-354.
Grimston, S. K. & Hay, J. G. 1986. The relationship among anthropometric and stroking characteristics of college swimmers. Medicine and Science in Sports and Exercise 18, 60-68.
Gullstrand, L. & Holmer, I. 1980. Fysiologiska tester av landslagssimmare: Anaerob energileveransmätningen av blodmjölksyra [The physiological tests for the national team swimmers: Measurement of anaerobic energy metabolism by blood lactate]. Simsport 3, 15-17.
Häkkinen, K. & Komi, P.V. 1985. Effect of explosive type strength training on electromyographic and force production characteristics of leg extensor muscles during concentric and various stretch-shortening cycle exercises. Scandinavian Journal of Sports Sciences 7 (2), 65-76.
Häkkinen, K., Komi, P. V. & Alen, M. 1985. Effect of explosive type strength training on isometric force- and relaxation time, electromyographic and muscle fibre characteristics of leg extensor muscles. Acta Physiologica Scandinavica 125: 587-600.
Hay, J. G. 1978. Swimming. In J. G. Hay (ed.), The Biomechanics of sports techniques. Englewood Cliffs, Prentice-Hall, New Jersey, 337-381.

Hay, J. G. & Guimares, A. C. S. 1983. A quantitative look at swimming Biomechanics. Swimming Technique 20 (2), 11-17.

Hay, J. G. 1987. Swimming Biomechanics: A brief review. Swimming Technique 23 (3), 15-21.

Hoffman, K. 1972. Stride length and frequency of female sprinters. Track Technique 48, 1522-1524.

Högberg, P. 1952. How do stride length and stride frequency influence the energy output during running? Arbeitsphysiologie 14, 437-441.

Hollander, A. P., de Groot, G., van Ingen-Schenau, G. J., Toussaint, H. M., de Best, H., Peters, W., Meulemans, A. & Schreurs, A. W. 1986. Measurement of active drag during crawl arm stroke swimming. Journal of Sports Sciences 4, 21-30.

Hollander, A. P., de Groot, G., van Ingen-Schenau, G. J., Kahman, R. & Toussaint, H. M. 1988. Contribution of the legs to propulsion in front crawl swimming. In B. E. Ungerechts, K. Wilke & K. Reischle (eds.), Swimming Science V. Human Kinetics, Champaign, Illinois, 39-43.

Holmer, I. 1974a. Propulsive efficiency of breaststroke and freestyle swimming. European Journal of Applied Physiology 33, 95-103.

Holmer, I. 1974b. Energy cost of arm stroke, leg kick, and the whole stroke in competitive swimming styles. European Journal of Applied Physiology 33, 105-118.

Hopper, R. T., Hadley, C., Piva, M. & Bambauer, B. 1983. Measurement of power delivered to an external weight. In A. P. Hollander, P. A. Huijing & G. de Groot (eds.), Biomechanics and Medicine in Swimming. Human Kinetics, Champaign, Illinois, 113-119.

Huber, G., Keul, J., Kinderman, W. & Stoklasa, L. 1978. Herzfrequenzen, Lactatspiegel und pH-Wert bei verschiedenen Trainingsformen im Kraulschwimmen [Heart rate, lactate mirror and pH values in different modes of training in crawl swimming]. Deutsche Zeitschrift für Sportmedizin 29, 282-291.

Hultman, E., Bergström, J. & McLennan Anderson, N. 1967. Breakdown and resynthesis of phosphorylcreatine and adenosine triphosphate in connection with muscular work in man. Scandinavian Journal of Clinical Laboratory Investigation 19, 56-66.

Jackson, A. S. & Pollock, M. L. 1978. Generalised equations for predicting body density of men. British Journal of Nutrition 40, 497-504.

Johns, R. A., Houmard, J. A., Kobe, R. W., Hortobágyi, T., Bruno, N. J., Wells, J. M. & Shinebarger M. H. 1992. Effects of taper on swim power, stroke distance, and performance. Medicine and Science in Sports and Exercise 24, 1141-1146.

Karpovic, P. V. 1935. Analysis of the propelling force in the crawl stroke.

Research Quarterly 6, 49-58.

Keskinen, K. L., Komi, P. V. & Rusko, H. 1989. Comparative study of Blood Lactate Tests in Swimming. International Journal of Sports Medicine 10, 197-201.

Kennedy, P., Brown, P., Chengalur, S. N., & Nelson, R. C. 1990. Analysis of male and female Olympic swimmers in the 100-meter events. International Journal of Sport Biomechanics 6, 187-197.

Knuttgen, H. C. 1961. Oxygen uptake and pulse rate while running with undetermined and determined stride lengths at different speeds. Acta Physiologica Scandinavica 52, 366-371.

Komi, P. V. 1973. Measurement of the force-velocity relationships in human muscle under concentric and eccentric contractions. In S. Cerguiglini (ed.), Biomechanics III. Basel: Karger, 224-229.

Lang, T. G. & Norris, K. S. 1966. Swimming speed of a Pacific bottle nose porpoise. Science 151, 588-590.

Letzelter, H. & Freitag, W. 1982. Geschwindigkeits- und Zugverhalten im 200-m Freistilschwimmen von Männern und Frauen der Europäischen Spitzenklasse [Speed and stroke characteristics in 200-m freestyle swimming of top level European men and women]. Leistungssport 6, 442-452.

Letzelter, H. & Freitag, W. 1983. Stroke length and stroke frequency variations in men's and women's 100-m freestyle swimming. In A. P. Hollander, P. A. Huijing & G. de Groot (eds.), Biomechanics and Medicine in Swimming. International Series on Sport Sciences, Human Kinetics, Champaign, Illinois, vol. 14, 315-322.

Luhtanen, P. & Komi, P. V. 1978. Mechanical factors influencing running speed. In E. Asmussen & K. Jorgenssen (eds.), Biomechanics 6B. University Park Press, Baltimore, 23-29.

Mader, A., Heck, H. & Hollmann, W. 1976. Evaluation of lactic acid anaerobic energy contribution by determination of post exercise lactic acid concentration of ear capillary blood in middle distance runners and swimmers. In F. Landing & W. Orban (eds.), Exercise Physiology. Symposia Specialists, Miami, Florida, vol. 4, 187-200.

Mader, A., Heck, H., Föhrenbach, R. & Hollmann, W. 1979. Das statische und dynamische Verhalten des Lactats und der Säure-Basen-Status im Bereich niedriger bis maximaler Azidosen bei 400- und 800-m-Läufern bei beiden Geschlechtern nach Belastungsabbruch [Static and dynamic composition of lactate and acid-base balance from low to maximal acidosis in 400- and 800-m runners of the two genders after loading]. Deutsche Zeitschrift für Sportmedizin 7, 203-211 & 8, 249-261.

Magel, J. R. 1970. Propelling force measured during tethered swimming in the four competitive swimming styles. Research Quarterly 41, 68-74.

Miller, D. I. 1975. Biomechanics of swimming. In J. H. Wilmore & J. F. Keogh (eds.), Exercise and Sport Sciences Reviews. Academic Press, Orlando, Florida, vol. 3, 219-248.

Monteil, K. M. & Rouard, A. 1992. Influence of the size of the paddles in front crawl stroke. In D. MacLaren, T. Reilly & A. Lees (eds.), Biomechanics and Medicine in Swimming, Swimming Science VI. E & F SPON, Chapman & Hall, London, 99-104.

Morgan, D. W. & Martin, P. E. 1986. Effects of stride length alteration on race walking economy. Canadian Journal of Applied Sport Sciences 11, 211-217.

Mustonen, S. 1987. Survo 84C User's Guide. University of Helsinki, Department of statistics. Helsinki.

Nelson, R. C., Dillman, C. J., Lagasse, P. & Bickett, P. 1972. Biomechanics of overground versus treadmill running. Medicine and Science in Sports 4, 233-240.

Nelson, R. C. & Gregor, R. J. 1976. Biomechanics of distance running: a longitudinal study. Research Quarterly 47, 417-427.

Nelson, R. C. & Pike, N. L. 1978. Analysis and comparison of swimming starts and strokes. In B. Eriksson & B. Furberg (eds.), Swimming Medicine IV. International Series on Sport Sciences, University Park Press, Baltimore, vol. 6, 347-360.

Nelson, R. C., Brown, P. L., Kennedy, P. W. & Chengalur, S. N. 1990. An Analysis of Olympic Swimmers in the 1988 Summer Games. Biomechanics Laboratory, Pennsylvania State University.

Pai, Y.-C., Hay, J. G. & Wilson, B. D. 1984. Stroking techniques of elite swimmers. Journal of Sports Sciences 2, 225-239.

Reilly, T. & Bailey, K. 1988. The relation between short-term power output and sprint performance of young female swimmers. Journal Human Movement Studies 14, 19-29.

Reischle, K. 1978. Cronofotografische Zuglängenregistrierung bei Delphin, Rücken und Kraul [Chronophotographic stroke length recordings of the dolphin, backstroke and crawl]. Beiheft zu Leistungssport 14, 31-49.

Rennie, D. W., di Prampero, P., Wilson, D. R. & Pendergast, D. R. 1973. Energetics of swimming the crawl. Fed. Proc., 32, 1125 (abs.).

Rivera, M. A., Albarran, M. A., & Torres, N. del c. 1986. Stroke rate, distance per stroke and velocity in infantile and juvenile swimmers. In M. Adrian & H. Deutsch (eds.), Biomechanics, The 1984 Olympic Scientific Congress Proceedings. Microfilm Publications, University of Oregon, Eugene, Oregon, 257-261.

Rompotti, K. 1957. A study of stride length in running. In D. Canham &

P. Diamond (eds.), International Track and Field Digest. Ann Arbor: Champions on Film, 249-256.

Saito, M. 1982. The effect of training on the relationships among velocity, stroke rate and distance per stroke in untrained subjects swimming the breaststroke. Research Quarterly for Exercise and Sport 53, 323-329.

Satori, J. 1974. Beobachtungen bei den Weltmeisterschaften der Schwimmer in Belgrad 1973 [Observations from the World Swimming Championships in Belgrade 1973]. Leistungssport 4 (2), 92-99.

Satori, J. 1975. Beobachtungen bei den XIII Europameisterschaften im Schwimmen in Wien 1974 [Observations from the XIIIth European Swimming Championships in Vienna 1974]. Leistungssport 5 (3), 222-230.

Satori, J. 1976. Beobachtungen bei den II Weltmeisterschaften im Schwimmen in Cali 1975 [Observations from the IInd World Swimming Championships in Cali 1975]. Leistungssport 6 (3), 210-217.

Satori, J. 1980. Beobachtungen bei den III Schwimm-Weltmeisterschaften in Berlin 1978 [Observations from the IIIrd World Swimming Championships in Berlin 1978]. Leistungssport 10 (1), 35-39.

Simon, G., Thiessmann, M., Clasing, D. & Frohberger, V. 1982. Ergometrie im Wasser; eine neue Methode der Leistungsdiagnostik [Ergometry in water: a new method for diagnostics of performance]. Deutsche Zeitschrift für Sportmedizin 33 (8), 254.

Sprague, H. A. 1976. Relationship of certain physical measurements to swimming speed. Research Quarterly 47, 810-814.

Sharp, R., Troup J. P. & Costill D. L. 1982. Relationship between power and sprint freestyle swimming. Medicine and Science in Sports and Exercise 14, 53-56.

Siri, W. E. 1961. Body composition from fluid spaces and density: analysis of methods in techniques for measuring body composition. National Academy of Science, National Research Council, Washington DC, 223-244.

Smith, G. A., McNitt-Gray, J. & Nelson, R. C. 1988. Kinematic analysis of alternate stride skating in cross-country skiing. International Journal of Sport Biomechanics 4, 49-58.

Swaine, I. & Reilly, T. 1983. The freely chosen swimming stroke rate in a maximal swim and on a biokinetic swim bench. Medicine and Science in Sports and Exercise 15, 370-375.

Thayer, A. L. & Hay, J. G. 1984. Motivating start and turn improvement. Swimming Technique 20, 17-20.

Toussaint, H. M., van der Helm, F. C. T., Elzerman, J. R., Hollander, P. A., de Groot, G. & van Ingen-Schenau, G. J. 1983. A Power Balance Applied to Swimming. In A. P. Hollander, P. A. Huijing &

G. de Groot (eds.), Biomechanics and Medicine in Swimming. Human Kinetics, Champaign, Illinois, 165-172.

Toussaint, H. M. 1990. Differences in propelling efficiency between competitive and triathlon swimmers. Medicine in Science and Sports and Exercise 22, 409-415.

Toussaint, H. M., de Looze, M. & van Roosem, B. 1990. The effect of growth on drag in young swimmers. International Journal of Sport Biomechanics 6 (1), 18-28.

Toussaint, H. M., Janssen, T. & Kluft, M. 1991. Effect of propelling surfaces size on the mechanics and energetics of front crawl swimming. Journal of Biomechanics 24 (3-4): 205-211.

Wakayoshi, K. 1988. Swimming techniques of Japanese elite swimmers. 1988 Seoul Olympic Scientific Congress, Abstract no 3, 319.

Wakayoshi, K., Nomura, T., Takahashi, G., Mutoh, Y. & Miyashita, M. 1992. Analysis of swimming races in the 1989 Pan Pacific Swimming Championships and Japanese Olympic Trials. In D. MacLaren, T. Reilly (eds.), Biomechanics and Medicine in Swimming; Swimming Science VI. E & FN SPON, London, 135-141.

Wakayoshi, K., Yoshida, T., Udo, M., Kasai, T., Moritani, T., Mutoh, Y. & Miyashita, M. 1992. A simple method for determining critical speed as swimming fatigue threshold in competitive swimming. International Journal of Sport Medicine 13, 367-371.

Walters, V. & Fierstine, H. L. 1964. Measurements of swimming speeds of yellow-fin tuna and wahoo. Nature, 202, 208-209.

Watkins, J. & Gordon, A. T. 1983. The effects of leg action on performance in the sprint front crawl stroke. In A. P. Hollander, P. A. Huijing & G. de Groot (eds.), Biomechanics and Medicine in Swimming. International Series on Sport Sciences, Human Kinetics, Champaign, Illinois, vol. 14, 310-314.

Weiss, M., Reischle, K., Bouws, N., Simon, G., & Weicker, H. 1988. Relationship of blood lactate accumulation to stroke rate and distance per stroke in top female swimmers. In B. E. Ungerechts, K. Wilke & K. Reischle (eds.), Swimming Science V. Human Kinetics, Champaign, Illinois, 295-303.

Wilkie, D. R. 1950. The relation between force and velocity in human muscle. Journal of Physiology of London 110, 249-280.

Williams, K. & Cavanagh, P. 1987. Relationship between distance running mechanics, running economy, and performance. Journal of Applied Physiology 63, 1236-1245.

Yeater, R. A., Martin, R. B., White, M. K. & Gilson, K. H. 1981. Tethered swimming forces in the crawl, breast and back strokes and their relationship to competitive performance. Journal of Biomechanics 14, 527-537.