

# A New Laboratory Test Method for Estimating Anaerobic Performance Characteristics with Special Reference to Sprint Running

Ari Nummela



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## ABSTRACT

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The present study was aimed at developing a new laboratory test method, which could be used to determine both the metabolic and neuromuscular components of maximal anaerobic running performance and which could provide training prescription for sports with short duration and high power output. A total of 60 male athletes (400-m, middle and long distance runners and power athletes), 8 female 400-m runners and 34 physically active men volunteered to participate in tests for the study. The new maximal anaerobic running test (MART) consisted of  $n \times 20$ -s runs on a treadmill with a 100-s recovery between the runs. The speed of the treadmill was increased after each consecutive run until exhaustion but the slope of the treadmill was kept constant ( $1^\circ$ ,  $3^\circ$ ,  $4^\circ$ ,  $5^\circ$  or  $7^\circ$ ). In order to determine the blood lactate vs.  $O_2$  demand curve, blood lactate concentration was measured at rest and after each run. The height of counter-movement jump was measured at rest ( $CMJ_{rest}$ ) and after exhaustion. Correlation and regression analyses revealed that the most important determinants of the maximal anaerobic work capacity were maximal running velocity on a track, power at  $10 \text{ mmol} \cdot \text{l}^{-1}$  blood lactate level ( $P_{10\text{mM}}$ ) and peak blood lactate concentration (peak BLA). Present results showed that the grade of the treadmill affects the results of the MART since maximal ( $P_{max}$ ) and submaximal power ( $P_{10\text{mM}}$  and  $P_{5\text{mM}}$ ) indices increased when the treadmill inclination increased from  $1^\circ$  to  $7^\circ$ . Furthermore, the relative weight of the metabolic component to determine the  $P_{max}$  increased and the relative weight of the force-velocity component of the neuromuscular system decreased with the increased grade in the MART. High  $P_{max}$ , peak BLA and contribution of anaerobic energy yield, as well as significant correlations between the corresponding variables of the MART and Wingate test, suggested that the MART is a valid maximal anaerobic running performance test. Reliability figures of the MART variables also indicated that the MART is a reliable test. Furthermore, the present results showed that sprint training increased the  $P_{max}$  in well-trained sprint runners. Moreover, correlation analyses showed that individual changes in submaximal power ( $P_{3\text{mM}}$ ), peak BLA,  $P_{max}$  and  $CMJ_{rest}$  were related to the volume of corresponding training methods, suggesting that the MART is a sensitive test method for sprint running.

Key words: anaerobic power, anaerobic capacity, blood lactate, sprint running, sprint training, athletes, treadmill test

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## LIST OF ORIGINAL ARTICLES

This dissertation is based on the following publications and the abstract, which will be referred to by their Roman numerals:

- I Rusko, H., Nummela, A. & Mero, A. (1993) A new method for the evaluation of anaerobic power in athletes. *Eur J Appl Physiol* 66: 97-101.
- II Nummela, A., Andersson, N., Häkkinen, K. & Rusko, H. (1996) Effect of inclination on the results of maximal anaerobic running test. *Int J Sports Med* 17, Suppl. 2: S103-S108.
- III Nummela, A., Alberts, M., Rijnthjes, R., Luhtanen, P. & Rusko, H. (1996) Reliability and validity of the maximal anaerobic running test. *Int J Sports Med* 17, Suppl. 2: S97-S102.
- IV Nummela, A., Mero, A., Stray-Gundersen, J. & Rusko, H. (1996) Important determinants of maximal anaerobic running performance in male athletes and non-athletes. *Int J Sports Med* 17, Suppl. 2: S91-S96.
- V Nummela, A., Mero, A. & Rusko, H. (1996) Effects of sprint training on the determinants of maximal anaerobic running performance. *Int J Sports Med* 17, Suppl. 2: S114-S119.
- VI Nummela, A. & Rusko, H. (1995) Repeatability of the maximal anaerobic running power test in athletes. *Third IOC World Congress on Sport Sciences, Congress Proceedings, Atlanta, GA, USA*, p 99.

## ABBREVIATIONS AND DEFINITIONS

ACSM formula	formula of the American College of Sports Medicine for determining the oxygen demand of inclined treadmill running and ergometer cycling
ADP	adenosine diphosphate
Aerobic power	maximum rate of ATP resynthesis via aerobic metabolism
Alactic capacity	total amount of ATP replenished via ~P hydrolysis during a specific type of short-term maximal exercise
Anaerobic capacity	maximum amount of ATP resynthesised via anaerobic metabolism during a short-term maximal exercise
Anaerobic power	rate of ATP resynthesis via anaerobic metabolism during a specific type of short-term maximal exercise
Anaerobic work capacity	total amount of work performed during an exhaustive work bout which is of a sufficient duration to maximise anaerobic ATP yield
Anaerobic%	the percentage contribution of anaerobic energy yield
ATP	adenosine triphosphate
BLa	blood lactate concentration
Bounding exercises	exercises which include vertical and horizontal jumps
CMJ <sub>decr</sub>	percentage decrease of the height of rise of centre of mass in the counter-movement jump during the MART
CMJ <sub>fatigue</sub>	mean height of rise of centre of mass of the two highest counter-movement jumps immediately after the MART
CMJ <sub>max</sub>	mean height of rise of centre of mass of the two highest counter-movement jumps in the MART
CMJ <sub>rest</sub>	mean height of rise of centre of mass of the two highest counter-movement jumps before the MART
CV	coefficient of variation
Extensive interval training	sprint training method which includes intervals from 100 m to 600 m at velocity

	below 80% of the maximum velocity of selected distance
Fatigue index	percentage decrease of the highest 5-s power output to the lowest 5-s power output in the Wingate test
FT muscle fibre	fast twitch muscle fibre
General endurance training	training method which includes warm-up runs and aerobic runs at a constant velocity
H <sup>+</sup>	hydrogen ion
Intensive interval training	sprint training method which includes intervals from 60 m to 600 m at the velocity of 80% - 95% of the maximum velocity of selected distance
Lactic capacity	total amount of ATP resynthesised via glycolysis during a specific type of short-term maximal exercise
MANOVA	multiple analysis of variance
MART	maximal anaerobic running test
Maximal anaerobic performance	ability to perform a specific type of short-term maximal exercise
O <sub>2</sub>	oxygen
Oxygen debt	net oxygen consumption during recovery i.e. excess post-exercise oxygen consumption
Oxygen deficit	difference between the estimated oxygen demand and measured oxygen uptake
Oxygen demand	estimate of the rate of total energy release in oxygen equivalents
$\Delta P$	difference between the $P_{\max}$ and $VO_{2\max}$
$P_{3\text{mM}}$	oxygen demand at 3 mmol · l <sup>-1</sup> blood lactate level in the MART
$P_{5\text{mM}}$	oxygen demand at 5 mmol · l <sup>-1</sup> blood lactate level in the MART
$P_{10\text{mM}}$	oxygen demand at 10 mmol · l <sup>-1</sup> blood lactate level in the MART
$P_{[10\text{mM}-3\text{mM}]}$	difference between the $P_{10\text{mM}}$ and $P_{3\text{mM}}$ in the MART
$P_{\max}$	maximal power expressed as oxygen demand in the MART
PCr	phosphocreatine
Peak BLa	the highest blood lactate concentration after exhaustive exercise
Peak power	the highest 5-s power output in the Wingate test
P <sub>i</sub>	orthophosphate
SD	standard deviation
SE	standard error of estimate
Short-term exercise	an exercise with a duration under 2 min

Speed training	sprint training method which includes runs from 20 m to 80 m > 95% of the maximum velocity
Sprint training	complex process which includes speed and speed endurance training as well as strength training in various combinations
Sprinting economy	running speed or power at submaximal blood lactate level
ST muscle fibre	slow twitch muscle fibre
Strength training	sprint training method which includes weight lifting series and repetitions such as 2 - 4 x 1 - 10 x 50% - 100% of one repetition maximum
$T_{an}$	oxygen demand at anaerobic threshold
Total work	total work performed in the Wingate test
$V_{20m}$	average velocity in the 20-m speed test with a running start on a track
$V_{30m}$	average velocity in the 30-m speed test with a running start on a track
$V_{400m}$	average velocity in the 400-m run
$VO_2$	oxygen uptake
$VO_{2max}$	maximal oxygen uptake

# 1 INTRODUCTION

Since Krogh & Lindhard (1920) introduced the concept of oxygen deficit, there have been numerous attempts using different methods to determine the anaerobic power and capacity. However, in contrast to the aerobic systems the anaerobic systems have proved to be a difficult metabolic construct to measure and there is no universally accepted method to evaluate the determinants of maximal anaerobic work capacity. Previous methods for determining the anaerobic power or anaerobic work capacity include vertical jump tests (Sargent 1924 cited by Vandewalle et al. 1987, Komi & Bosco 1978, Bosco et al. 1983), a staircase running test (Margaria et al. 1966), and cycle ergometer tests (Ayalon et al. 1974, Szögy & Cherebetiu 1974). Different running tests on a treadmill have also been applied for untrained and trained subjects (Thomson & Garvie 1981, Schnabel & Kindermann 1983). As reviewed by Vandewalle et al. (1987) none of these tests has enabled accurate measurement of all the different determinants of maximal anaerobic performance, and what is an even greater defect, they provide limited information for prescription of training in sprint athletes.

The anaerobic performance test should be reliable, valid and practical to measure anaerobic performance characteristics and the results of the test should be useful for the subjects in their training. If the anaerobic performance test must be performed by an average population, it may be better to select a simple test with short duration instead of a more difficult and painful test like an all-out or constant load test with a duration of over 60 s. The latter tests are also questionable since the involvement of aerobic processes increases with the duration of exercise. In elite athletes, the magnitude of training effects is sometimes smaller than the normal variation of test results. Quite often well trained athletes are able to estimate their performance capacity at higher accuracy than the anaerobic performance tests. Furthermore, the anaerobic performance test is questionable for elite athletes if the only result is the

estimate of the anaerobic power or capacity: a sports specific field test would probably be just as useful. Therefore, in order to increase the usefulness of the test, it should give a reliable and valid estimate of the most important determinants of the maximal anaerobic performance, it should be utilised for training, and it should be sport-specific e.g. vertical jump test for jumpers and volleyball players, cycle ergometer test for cyclists and treadmill test for runners and other sports where running plays an important role.

It is a common experience in a number of different sports that the proper application of anaerobic training improves performance in intense exercise of short duration. Both significant and non-significant effects of training have been reported in untrained subjects (Jacobs et al. 1987, Nevill et al. 1989, Medbø & Burgers 1990). However, if initially untrained subjects are used, the increase in anaerobic power and capacity can easily be attained by almost any method if training intensity sufficiently exceeds the normal daily activity of an individual muscle. In well-trained subjects and especially in elite sprint athletes improvements in anaerobic capacity and power are much more limited and it is very difficult to determine accurately the type, intensity and volume of training that is optimal for each individual during a certain period of time. There is also a lack of information about how the different kinds of training (e.g. intensive and extensive interval training, strength and power training, endurance training) affect the components of maximal anaerobic performance in elite sprint athletes.

The present study was undertaken to develop a new laboratory test method, which could be used to determine both the metabolic and neuromuscular components of maximal anaerobic performance. It was also planned that submaximal exercise intensities should be included so that the results could provide training prescription for sports with short duration (30 - 120 s) and high power output.

## **2 REVIEW OF THE LITERATURE**

### **2.1 Determinants of maximal anaerobic performance**

Mechanical work output which is primarily dependent on the anaerobic capacity may be termed anaerobic work capacity. Anaerobic work capacity can be defined as the total amount of work performed during an exhaustive work bout which is of a sufficient duration to maximise the anaerobic ATP yield (Green 1994). Anaerobic power is the rate of ATP resynthesis via anaerobic energy metabolism during a specific type of short-term maximal exercise (Green & Dawson 1993, Green 1994). The subsequent translation of anaerobic power to mechanical power output is determined by force and velocity factors as well as factors which influence biomechanical efficiency during the movement. The anaerobic work capacity is the product of the time over which this mechanical power output is maintained.

While the association of acidosis with muscle fatigue is clear in short-term maximal exercises, the exact mechanism is far less certain. The problem is that a large number of both biochemical and biophysical changes occur at the same time that fatigue is developing. Cooke & Pate (1990) have suggested that the accumulation of three direct products of ATP hydrolysis (ADP, Pi and H<sup>+</sup>) affects the contractile interaction. During moderate fatigue all three increase by approximately a factor of 10, although exact basal concentrations and observed changes depend upon both muscle type and degree of fatigue (Cooke & Pate 1990).

In theory, performance in short-term maximal exercises could be explained by several factors: (1) the rate and capacity of glycolysis and lactic acid production (Sahlin et al. 1981, Thomson & Garvie 1981); (2) the stores and utilisation of phosphocreatine (PCr) in muscles (Hirvonen et al. 1987, Balsom et al. 1993); (3) the buffer capacity of muscles and blood (Parkhouse & McKenzie



1984, Denis et al. 1992); (4) the rate of hydrogen ion and lactate removal, diffusion and re-use during exercise (Mainwood & Renaud 1985); (5) oxygen stores (Di Prampero et al. 1983); (6) oxygen uptake on-response and/or maximal oxygen uptake (Margaria et al. 1963, Mero et al. 1993, Nummela & Rusko 1995); (7) force-generating capacity of the neuromuscular system (Mero & Komi 1986, Denis et al. 1992); (8) mechanical efficiency (Kaneko et al. 1981, Aura & Komi 1986, Bosco et al. 1986); and (9) motivational factors. The items from 1 to 4 are linked to anaerobic metabolism and the anaerobic capacity is influenced by those factors. The anaerobic power is mainly influenced by items 1 and 2. All factors in this list influence the anaerobic work capacity in short-term maximal exercises but the mechanical power consisted mainly of items 1 - 2 and 7 - 8.

### 2.1.1 Metabolic factors

The ATP and PCr stores in both untrained and trained muscles are limited: 4 - 7 mmol · kg<sup>-1</sup> and 15 - 25 mmol · kg<sup>-1</sup> wet weight, respectively (Rehunen et al. 1982, Hirvonen et al. 1987). Hirvonen et al. (1987) have suggested that in the 100-m sprint performance depends on the ability to use high-energy phosphates and that the decrease in running speed begins when decreased PCr stores could no longer cover the high need of ATP. The lactic capacity may be a limiting factor during exhaustive sprints since the depletion of PCr is almost complete in the 400-m run (Hirvonen et al. 1992). At the same time no more than a 40% decrease in ATP concentration has been observed (Hultman & Sjöholm 1983, Hirvonen et al. 1992).

Glycolysis begins within 5 s after the initiation of exercise, as does a reduction in ATP and PCr stores (Hultman & Sjöholm 1983). In short-term exercise, lactic acid production will be directly related to the mass of active muscles and the number of stimulatory impulses delivered to the muscles to activate them (Maxwell et al. 1977, Stainsby & Eitzman 1986). Muscle fibre types, blood flow and its distribution, and effectors of membrane lactic acid transport also have a role in the net release of lactic acid from muscle to blood (Stainsby & Brooks 1990).

Although skeletal muscle is considered to be the major site of lactate formation, in some circumstances, it is also responsible for significant net lactate removal from the blood (Richter et al. 1988). The basic determinants of lactic acid removal from the blood by active muscle appear to be the concentration of lactate in the blood and the activity level (Stainsby & Brooks 1990). The higher the blood lactate concentration and activity, the greater the net removal of lactate from the blood will be. Although the liver and heart have been generally accepted to be the major sites of lactic acid removal (Stainsby & Brooks 1990), the precise quantification of the removal by inactive muscles, liver, heart, skin and other tissues is not yet possible. This removal of lactic acid from the blood is also significantly influenced by effectors of glycolysis, glycogenolysis, and gluconeogenesis (e.g. epinephrine and glucagon). The data available on human subjects and laboratory animals suggest that training induced decreases in

circulating blood lactate levels during given submaximal aerobic exercise intensity resulted from an increased blood lactate clearance rate (Saltin 1990, Brooks 1991).

Hydrogen ions are formed in an equivalent amount to lactate and will decrease intracellular pH. This decrease could limit muscular force production and cause muscle fatigue through inhibition of glycolysis and/or excitation-contraction coupling (e.g. Mainwood & Renaud 1985). The extent of the decrease in muscle pH during muscular activity is dependent upon both the amount of released H<sup>+</sup> ions and on the buffer capacity of the muscle. An increased buffer capacity would enable the muscle to accumulate more lactic acid until a given pH decrease is obtained. This would enhance the anaerobic energy production and thus improve the anaerobic work capacity. Furthermore, Sahlin & Henriksson (1984) have indicated that skeletal muscle buffer capacity can be increased by training in man.

Depending on the muscle mass involved in the exercise and the training background, the actual amount of the alactic and lactic components of the anaerobic capacity varies slightly (Table 1). The relative importance of the anaerobic energy yield to exercise performance will differ according to the intensity and duration of the exercise. The alactic capacity would be important to activities characterised by the maintenance of maximum power output from 5 to 15 s, whereas the lactic capacity and the mechanisms that determine it become more important as the duration of the maximal activity is from 30 s to 120 s. Data demonstrating a complete usage of anaerobic capacity in 1 - 2 min are available (Medbø et al. 1988, Medbø & Tabata 1989). The highest peak blood lactate concentrations have also been measured following the maximal exercises of 1 - 2 min (Hermansen 1971, Kindermann & Keul 1977). In maximal exercises of 60 s duration, the contributions to energy output from aerobic processes have ranged from 28% to 48% in various studies for trained and untrained subjects (Thomson & Garvie 1981, Medbø & Tabata 1989, Nummela & Rusko 1995). However, the sprinters have used more the anaerobic and endurance athletes more the aerobic pathways for energy production even during short-term maximal exercises (Nummela & Rusko 1995).

TABLE 1. Components of the anaerobic capacity determined by the oxygen deficit (adapted from Saltin 1990). Abbreviations: Hb = haemoglobin; Mb = myoglobin; O<sub>2</sub> = oxygen; ATP = adenosine triphosphate; PCr = phosphocreatine.

Components	O <sub>2</sub> equivalents (ml · kg <sup>-1</sup> )	Percentage of total (%)
Hb and Mb O <sub>2</sub> stores	5 - 6	8 - 10
ATP and PCr	15 - 16	22 - 30
Glycolysis	30 - 48	60 - 70
Total capacity	50 - 70	100

### 2.1.2 Neuromuscular factors

The power produced during a muscle shortening depends on both force and velocity characteristics of the neuromuscular system. With respect to the neuromuscular aspects of force and velocity, several factors are important. Muscle strength is usually related to the cross-sectional area of the muscle so that bigger muscles are able to produce greater force output than muscles with a small cross-sectional area (Maughan et al. 1983). Although cross-sectional area is related to muscle strength, other factors like neural adaptation to specific training may be more important phenomena in increasing muscle force-generating capacity than muscle hypertrophy (Komi 1979). The observation that several untrained subjects were not able to activate their muscles fully before training suggests that there is a functional reserve in the nervous system that is not readily available for use (Sale 1986). This would explain in part the great initial increases in muscle strength of untrained subjects during their early weeks of strength training (Häkkinen 1989).

Muscle fibre composition also has an influence on the mechanical aspects of muscle function. Fibres are usually classified as slow twitch (ST) and fast twitch (FT) fibres according to their mechanical properties (Gollnick et al. 1972, Karlsson 1979). A muscle composed primarily of FT fibres has a shorter electromechanical delay, a shorter time to peak tension and shorter relaxation times compared to ST type muscles (Karlsson 1979, Komi 1979). A number of studies have demonstrated that sprint athletes have a higher proportion of FT fibres in their active muscle groups than endurance athletes (Gollnick et al. 1972, Costill et al. 1976, Forsberg et al. 1976) suggesting that not only a genotype but also physical training may affect the muscle structure of an individual athlete. Strength training induced changes in the muscle cross-sectional area take place in both fibre types, although it may be greater in FT muscle fibres (Komi et al. 1982, Houston et al. 1983). However, the increased muscle strength would not be dependent on muscle fibre distribution (Häkkinen et al. 1981, Häkkinen 1989).

Muscle elasticity plays an important role in human locomotion by improving the power output in maximal effort and efficiency of locomotion (Asmussen & Bonde-Petersen 1974, Bosco et al. 1982, Aura & Komi 1986). In situations where the muscle function occurs as a stretch-shortening cycle, part of the imposed energy during stretching may be stored as potential energy and can then reappear during a subsequent shortening of the muscle (Cavagna 1977, Komi 1984). Power type strength training may have an effect on neuromuscular factors in stretch-shortening type of exercises like running and jumping since the nervous system plays an important role in regulating muscle stiffness and thus utilisation of muscle elasticity (Aura & Komi 1986). Muscle stiffness and metabolic efficiency have been shown to increase as a result of various types of jumping exercises (Kyröläinen et al. 1991).

A commonly used method to establish differences between individuals with respect to the economy of distance running is to measure oxygen consumption during a steady-state exercise (Morgan et al. 1989). An approach to evaluate the economy of sprint running is to compute the actual mechanical

efficiency. However, this is difficult to carry out because of the calculations of the exact work and input of energy. Some previous studies (Cavagna & Kaneko 1977, Kaneko et al. 1981) have suggested that the efficiency of positive work increases with running velocity, while other reports observed no differences in the efficiency of running throughout the whole velocity range (Ito et al. 1983) or that the efficiency decreases with increasing running velocity (Kaneko et al. 1985). Kaneko et al. (1985) also observed that mechanical efficiency was higher in distance runners compared to sprint runners at low running speeds, but that this relationship tended to reverse at higher velocities showing the specificity of training.

As suggested previously, economy of sprint running can also be evaluated indirectly by measuring blood lactate levels while performing submaximal sprints (Schnabel & Kindermann 1983, Mero et al. 1992). The idea is that the less lactate accumulated in the blood at a certain submaximal speed the better the economy is of sprint running. Possible reasons for the lower lactate concentration are more efficient utilisation of ATP and PCr stores and/or aerobic energy production, and better mechanical and/or biochemical efficiency of the neuromuscular system. This approach is widely used in practice to evaluate the economy of sprint running.

## **2.2 Measurement of anaerobic power and capacities**

### **2.2.1 Anaerobic power tests**

The power produced during muscular shortening depends on both force and velocity characteristics of the neuromuscular system. The test methods for determining the mechanical and anaerobic power include vertical jump tests (Sargent 1924 cited by Vandewalle et al. 1987, Komi & Bosco 1978, Bosco et al. 1983), a staircase running test (Margaria et al. 1966) and cycle ergometer tests (Ayalon et al. 1974, Szögy & Cerebetiu 1974). Vertical jump tests were designed to assess the capability of the leg extensor muscles to generate mechanical power within a short period of time. Because of its high reproducibility ( $r > 0.92$ ) and simplicity, the vertical jump test is suitable for evaluating the anaerobic power of both athletes and normal population (Bosco et al. 1983, Vandewalle et al. 1987). The mechanical power in a 60-s jumping test was observed to be higher than the power in a 60-s all-out cycle ergometer test and in a staircase running test, probably because the utilisation of elastic energy is highly involved in the jumping test (Bosco et al. 1983). Since the validity of the jumping power calculation is questionable, it is simpler to consider only the value of the jumping height. The height of the vertical jump is highly correlated with peak power on an isokinetic cycle ergometer (Davies & Young 1984), the peak power of the Wingate test (Maud & Schultz 1986) and sprinting a 60-m dash (Bosco et al. 1983). The high correlation between the tests suggests that the high power of the leg extensor muscles is an important determining factor in all of these tests and the results of the vertical jump test can very likely be

extended to actual movements in various sport activities, where the force-velocity properties of thigh muscles becomes evident.

The staircase running test can also be considered a simple and highly reproducible anaerobic power test. The test-retest correlation coefficient has been between 0.85 (Ayalon et al. 1974) and 0.90 (Sawka et al. 1980). The problem is, however, that the test is not very sport specific and therefore it is not practical and suitable for athletes. The Wingate anaerobic test was also designed to be simple to perform and administer without the need for a particularly skilled subject or personnel. It has been widely used to describe both anaerobic power and capacity in athletic and non-athletic populations (Bar-Or 1987). The test-retest reliability coefficient of peak power by means of the Wingate test has ranged from 0.89 to 0.98 for different subjects and under various conditions (Dotan & Bar-Or 1983, Bar-Or 1987). Since the correlations between power indices of the Wingate test and various anaerobic performance tests are quite high, one may conclude that the Wingate test is a valid anaerobic test, but previous studies have suggested that the correlations were not high enough for using the Wingate test as a predictor of success in specific sport tasks like skating and running (Tharp et al. 1985, Watson & Sargeant 1986, Bar-Or 1987).

The exact measurement of mechanical power in running is not possible due to the complexity of the running performance. Therefore, the average running speed during a short distance has been used to describe maximal running power in some studies (e.g. Bosco et al. 1983). There is a clear relationship between force production and stride length in running as well as between the speed of running and contact time (Mero et al. 1992). Therefore, if the stride characteristics are measured during running, the description of force-velocity properties of the subject becomes more precise.

### 2.2.2 Anaerobic capacity tests

A method of measuring a subject's anaerobic capacity is not yet available. Three main routes, oxygen debt, now termed excess post-exercise oxygen consumption, peak post-exercise blood lactate level, and oxygen deficit, have been tried to quantify the anaerobic capacity, but several objections on theoretical grounds can be made against each trial. The alactic oxygen debt has been suggested to be a reliable measure of alactic capacity (Roberts & Morton 1978). However, despite the causal link between oxygen supply and PCR resynthesis, a portion of the alactic oxygen debt can also be attributed to the replenishment of haemoglobin and myoglobin O<sub>2</sub> stores (Hermansen et al. 1984). Several reviews have provided a historical perspective and critique against the O<sub>2</sub> debt as a measure of anaerobic capacity (Gaesser & Brooks 1984, Hermansen & Medbø 1984, Green & Dawson 1993), with the conclusion that the O<sub>2</sub> debt is not a valid measure of anaerobic capacity.

### Peak post-exercise blood lactate level

Measurement of lactate in the blood after exhaustive exercise has frequently been used, and Margaria et al. (1963) have gone the furthest in using such a measure to estimate the anaerobic energy release. Significant relationships have been demonstrated between peak blood lactate concentration and running performances over 400 m (Ohkuwa et al. 1984, Lacour et al. 1990, Nummela et al. 1992) and 800 m (Lacour et al. 1990) as well as in treadmill running over 30 to 60 s (Fuyitsuka et al. 1982, Cheatham et al. 1986). Opposite results, however, have also been reported (Hirvonen et al. 1992). Higher peak blood lactate values have been reported for sprint and power athletes than for endurance athletes or untrained individuals (Komi et al. 1977, Thomson & Garvie 1981). Moreover, peak blood lactate has been shown to increase as a result of high intensity training (Ready et al. 1981, Sharp et al. 1986, Jacobs et al. 1987).

Despite these findings there are several difficulties with this method. One is identifying when an equilibrium between muscle and blood lactate concentration exists. Other problems are the variability of dilution space for lactate and of lactate's turnover rate (Hermansen & Stensvold 1972). Before an equilibrium is attained between muscle and blood and the lactate is evenly distributed in the various water spaces of the body, a large fraction of the lactate has been metabolised. Thus, although it is widely agreed that lactate in the blood reflects the amount of glycolytic energy production, it is equally true that it can give only a rough estimate of anaerobic energy yield.

### Oxygen deficit

In a review, Saltin (1990) claimed that  $O_2$  deficit is the only method with the potential to quantify anaerobic capacity. According to the assumption that energy expenditure increases linearly with increasing exercise intensity, the  $O_2$  demand at exercise intensities over the maximal  $O_2$  uptake can be estimated by linear extrapolation of the  $VO_2$  power output relationship determined at submaximal power outputs (Hermansen & Medbø 1984). Then the  $O_2$  deficit is calculated as the area between the estimated  $O_2$  demand and the  $VO_2$  asymptote over the exercise duration and is considered to reflect the breakdown of PCr, the anaerobic catabolism of carbohydrate, as well as the use of  $O_2$  stores (Åstrand & Rodahl 1986).

Maximal  $O_2$  deficit values reported for humans vary from  $33 \text{ ml} \cdot \text{kg}^{-1}$  in prepubescent males (Eriksson et al. 1973) to over  $80 \text{ ml} \cdot \text{kg}^{-1}$  in sprint athletes (Medbø et al. 1988, Medbø & Burgers 1990, Scott et al. 1991). A significant correlation between  $O_2$  deficit and 300 m sprinting performance and 2 to 3 min of treadmill running has been observed (Scott et al. 1991) suggesting that  $O_2$  deficit is a valid method for determining the anaerobic capacity, although non-significant correlation between  $O_2$  deficit and running performances over 400 m to 1500 m has also been reported (Green & Dawson 1993). The validity of  $O_2$  deficit measurement is confirmed by the findings that sprint-trained athletes have greater  $O_2$  deficit values than endurance-trained athletes (Hermansen &

Medbø 1984, Scott et al. 1991, Nummela & Rusko 1995) and that O<sub>2</sub> deficit can be increased by high-intensity training (Medbø & Burgers 1990).

However, there are also problems with the O<sub>2</sub> deficit. The measurement of O<sub>2</sub> deficit is based on the assumption that O<sub>2</sub> demand at supramaximal intensities can be extrapolated from submaximal VO<sub>2</sub> measurements. Such an assumption is likely to underestimate the true energy expenditure during maximal work because mechanical efficiency may be lower in supramaximal than in submaximal exercises (Luhtanen et al. 1989, 1990). As reviewed by Green & Dawson (1993) further research is required to establish the utility of O<sub>2</sub> deficit within homogeneous, high performance athletic populations.

### Anaerobic running performance tests

Previous methods for measuring the anaerobic running performance include all-out and constant load tests on a treadmill (Thomson & Garvie 1981, Schnabel & Kindermann 1983) and on a track (Borsetto et al. 1989). The constant speed tests were based on the rationale that time to exhaustion is primarily a function of anaerobic capacity. The problems are, however, that the involvement of aerobic processes increase as the duration of the exercise increases, and the mechanical efficiency of supramaximal exercises is difficult to assess (Di Prampero 1981, Vandewalle et al. 1987). Schnabel & Kindermann (1983) determined the glycolytic energy expenditure from the post-exercise blood lactate level and alactic anaerobic capacity was estimated by measuring the blood lactate concentration after a 40-s submaximal run of fixed duration and velocity. The evaluation of alactic anaerobic capacity was based on the assumption that during the submaximal run alactic and lactic energy release complement each other. Regression analysis revealed that net blood lactate accumulation in the 40-s run and peak blood lactate concentration in the exhaustive constant speed test explained 87% of the variability of the exhaustion time in the constant speed test (Schnabel & Kindermann 1983). Although the time to exhaustion in the constant load test has shown a tendency to increase with the increased maximal anaerobic running performance it is not accurate enough to be utilised in a homogeneous high performance athletic population (Schnabel & Kindermann 1983, Mero et al. 1993).

Thomson & Garvie (1981) introduced a treadmill test in which the velocity was determined so that exhaustion was elicited in just over a minute. The progressive lengthening of the sprint intervals allowed the measurement of the aerobic and anaerobic energy yield while the constant load permitted calculation of alactic energy yield. The estimated anaerobic energy expenditure was different between the sprint and endurance athletes and untrained subjects. The determined anaerobic capacity was correlated positively with the individual sprinting performance over 329 m (Thomson & Garvie 1981), suggesting that the test was a valid method to evaluate anaerobic capacity. Since the calculated alactic and lactic anaerobic capacity include so many assumptions and the repeatability and reliability of the test is unknown, further research is required to show that the test provides a reliable and valid measure of anaerobic capacity.

### 2.3 Effect of training on anaerobic performance characteristics

Cross-sectional studies have shown that sprint athletes have better lactic capacity than endurance athletes or untrained subjects (Thomson & Garvie 1981, Schnabel & Kindermann 1983, Medbø & Burgers 1990). The difference in alactic capacity, however, is not so clear. Rehunen et al. (1982) observed that there is no difference in ATP and PCr stores in resting muscles between endurance and sprint trained athletes but during an exhaustive exercise the depletion of the PCr stores was more complete in sprinters than in endurance athletes. In addition, indirect estimations of alactic energy yield also support the finding that the utilisation of phosphagen stores is better in sprinters than for untrained subjects or endurance athletes (Thomson & Garvie 1981, Schnabel & Kindermann 1983).

Peak power in the all-out test (Denis et al. 1992) and in vertical jumps (Bosco & Komi 1982, Paavolainen et al. 1994) have been better in sprinters than for the endurance athletes suggesting that force-velocity characteristics are better for sprinters. On the other hand, high maximal oxygen uptake has been shown to be of minimal advantage in short-term maximal exercise (Schnabel & Kindermann 1983, Nummela & Rusko 1995), although in over one minute of sprinting the amount of energy from aerobic sources has been estimated to be up to 30% - 45% of the total energy requirement (Åstrand & Rodahl 1986, Nummela & Rusko 1995).

It is generally accepted that sprint training will result in improvements in the ability to perform sprint exercise. However, the mechanism of adaptation and the effect of different exercises on the metabolic and neuromuscular components of the maximal anaerobic performance is poorly understood. Current knowledge of sprint training effects is based on cross-sectional studies and studies where subjects have been untrained. However, the training response of an initially untrained subject is different than that of an elite athlete. In untrained subjects, an 8-week period of sprint or interval training has previously been shown to result in improvements of 6% - 28% in sprint performance (Sharp et al. 1986, Nevill et al. 1989). On the other hand, Häkkinen (1989) has observed that in strength athletes the increase in muscular strength is less than 10% during a 12-week period of intensive strength training.

Another important aspect of scientific research in sprint training is that anaerobic work capacity should be considered as a complex requirement of the body involving different but strictly related and integrated metabolic and neuromuscular systems. In order to improve the anaerobic performance the training should include speed work, aerobic and anaerobic type of exercises as well as strength training in various combinations during the training periods. However, in most sprint training studies the training is simple and consists of intervals with various combinations of intensity, frequency and duration (Table 2). Table 2 shows that anaerobic type of training improves anaerobic capacity and power (Jacobs et al. 1987, Nevill et al. 1989, Medbø & Burgers 1990); has beneficial effects on glycolytic enzymes (Roberts et al. 1982, Cadefau et al. 1990); increases the number and area of FT fibres (Jacobs et al. 1987, Cadefau et al.



1990); and even increases the maximal oxygen uptake (Fox 1973, Ready et al. 1981, Mero et al. 1993) in trained and untrained subjects.

TABLE 2. Summary of some data in the literature on sprint training effects. Abbreviations: UT = untrained;  $VO_{2max}$  = maximal oxygen uptake; peak BLA = peak blood lactate concentration after exhaustive exercise; PFK = phosphofructokinase; FT% = percentage of fast twitch fibres; SDH = succinate dehydrokinase; LDH = lactate dehydrokinase; MDH = malate dehydrokinase; GAPDH = glyceraldehyde dehydrokinase; MLa = muscle lactate after exhaustive exercise; MpH = muscle pH after exhaustive exercise; PCr = phosphocreatine; Mb = myoglobin; CS = citrate synthase; BpH = blood pH after exhaustive exercise;  $Th_{aer}$  = aerobic threshold;  $Th_{an}$  = anaerobic threshold.

Reference	Training	Subjects	Training effects
Fox 1973	8 weeks 3 times/week 19x30s	16 UT	$VO_{2max}$ ↑, alactic $O_2$ debt ↑, lactic $O_2$ debt ±0, economy ±0
	7x2min	10 UT	$VO_{2max}$ ↑, alactic/lactic $O_2$ debt ↑, economy ↑
Fox et al. 1977	8 weeks 3 times/week 19x30s	15 UT males	$VO_{2max}$ ↑, peak BLA ±0, sub-maximal BLA ↓, alactic power ±0
	7x120s	15 UT males	$VO_{2max}$ ↑, peak BLA ±0, sub-maximal BLA ↓, alactic power ±0
Ready et al. 1981	6 weeks 3 times/week 10x1min	9 UT females	$VO_{2max}$ ↑, peak BLA ↑, $O_2$ debt ↑, time to exhaustion ↑
Fournier et al. 1982	3 months 4 times/week sprint training	6 adolescent boys	PFK ↑, FT% ±0, FT area ±0, SDH ±0, $VO_{2max}$ ↑
Roberts et al. 1982	5 weeks 3-4 times/week 8x200m	4 UT males	time to exhaustion ↑, PFK ↑, LDH ↑, MDH ↑, phosphorylase ↑, GAPDH ↑, SDH ±0
Sharp et al. 1986	8 weeks 4 times/week 8x30s	8 UT males	$VO_{2max}$ ↑, MLa ↑, MpH ±0, peak BLA ↑, PCr ±0, PFK ↑, buffer capacity ↑, peak torque ↑
Jacobs et al. 1987	6 weeks 2-3 times/week	11 UT (7 males 4 females)	Wingate ±0, BLA ↑, Mb ↓, CS ↑, PFK ↑, FT% ↑
Nevill et al. 1989	8 weeks 2x30s 2 times/week 6-10x6s once a week 2-5x2min once a week	4 male 4 female endurance athletes	peak power in 30s sprint ↑, MLa ↑, BpH ↓, buffer capacity ±0
Jansson et al. 1990	6 weeks 2-3 times/week 2→6x15s + 2→6x30s	8 UT males	FT% ↑
	3x30s	7 UT males	FT% ±0
Cadefau et al. 1990	8 months sprint training	11 male 5 female young athletes	sprint performance ↑, FT/ST area ↑, FT% ↑, glycogen ↑, SDH ↑, PFK ↑, phosphorylase ↑, pyruvate kinase ↑, glycogen synthase ↑
Medbø & Burgers 1990	6 weeks 3 times/week 3x2min or 8x20s	5 UT males 7 UT females	$O_2$ deficit ↑, BLA ±0
Mero et al. 1993	5 months sprint training	20 male 400m runners	$VO_{2max}$ ↑, $Th_{aer}$ ↑, $Th_{an}$ ↑, BLA ↑, time to exhaustion ↑, alactic/lactic $O_2$ debt ±0

### 3 PURPOSE OF THE STUDY

The general aim of this research programme was to develop a reliable and practical laboratory test method to determine different components of maximal anaerobic running performance. The new maximal anaerobic running test (MART) was planned to include submaximal running intensities so that the results could be useful for training in sports where the duration of competition is short and running plays a major role.

In order to establish the reliability of the MART, physically active men and sprint athletes performed the MART twice within one week (III, VI). The validity of the MART was determined by measuring aerobic and anaerobic energy yield during the MART (II - III); by comparing the results of the MART and Wingate test in physically active men (III); by comparing the results of the MART between the different groups of athlete (IV); and by investigating the effects of sprint training on the results of the MART (V).

Special attention was given to provide answers to the following questions:

1. Whether the selected neuromuscular and metabolic variables of the MART could be used to predict the maximal anaerobic running performance (I, IV).
2. Whether the different inclinations of treadmill affect the results of the MART (II).
3. What the contribution of anaerobic energy yield in the MART is (II, III).
4. Whether the corresponding variables of the MART and Wingate test correlate with each other (III).

5. Do male athletes with different training background differ in their anaerobic performance characteristics determined by the MART (IV).
6. Whether the first and second MART give similar results on all variables of the MART in physically active men and trained male athletes (III, VI).
7. Is the MART sensitive enough to reflect the effects of the various exercise types of sprint training (V). The main research hypotheses were that extensive interval training increases the sprint running velocity at submaximal levels of blood lactate and intensive intervals at maximal or near maximal levels of blood lactate concentration. Furthermore, bounding and strength training were expected to increase the height of rise of the centre of mass in vertical jumps.

## 4 MATERIAL AND METHODS

### 4.1 Subjects

A total of 94 male and 8 female subjects volunteered to participate in tests for the study. Their age ranged from 16 to 40 years. Twenty-seven of the men and all of the women were 400-m runners or hurdlers, 8 were middle distance runners (800 m - 1500 m), 11 long distance runners (5000 m - marathon), 14 power athletes (5 sprint runners, 7 decathlonists, a triple jumper and a Finnish baseball player), and 34 were physically active men. All athletes had engaged in regular training almost daily, from 4 to 14 hours per week and for 3 to 15 years. The training of the 400-m runners had consisted of short sprints, interval runs, bounding exercises, weight lifting as well as light aerobic endurance training. The training of the power athletes had been very much similar than that of the 400-m runners. The major difference was that the power athletes had concentrated more on bounding exercises and strength training and they had had less interval and endurance training in their training programme than the 400-m runners. The middle distance runners had concentrated on improving their anaerobic and aerobic endurance characteristics with interval and endurance training. In addition, some of them had included strength and power work in various combinations in their training programme. Aerobic endurance training had predominated the training of the long distance runners. Less than 10% of their total training time had consisted of interval runs and strength training. Most of the physically active men were physical education students who had practised different kinds of sports for recreation.

Table 3 summarises physical characteristics, age, and personal best results of the subjects in each study. Prior to the measurements taken in this study the subjects were fully informed of all the risks and possible discomfort associated with the experiments before they gave their written consent to participate. This

study was approved by the Ethics Committee of the University of Jyväskylä, Jyväskylä, Finland.

TABLE 3. Mean ( $\pm$  SD) age, height, and body mass of the subject groups. Range of personal best result in different events are also shown on the table. Abbreviations: MD runners = middle distance runners; LD runners = long distance runners.

Study / Subjects (n)	Age (years)	Height (cm)	Body mass (kg)	Personal best
Female sprinters (8) STUDY I	21.3 $\pm$ 4.2	168.4 $\pm$ 4.3	58.4 $\pm$ 5.1	400m: 52.71-57.31
400-m runners (13) STUDY II	24.5 $\pm$ 3.3	183.0 $\pm$ 5.5	73.1 $\pm$ 5.0	400m: 47.99-54.70
Physically active (10) STUDY III	24.4 $\pm$ 2.7	179.5 $\pm$ 4.8	71.2 $\pm$ 5.8	-
Physically active (13) STUDY IV	24.9 $\pm$ 3.4	177.3 $\pm$ 4.1	70.7 $\pm$ 5.8	-
400-m runners (21)	25.2 $\pm$ 4.4	184.1 $\pm$ 5.9	74.3 $\pm$ 5.7	400m: 44.82-52.44
MD runners (8)	25.6 $\pm$ 5.5	180.0 $\pm$ 3.9	70.8 $\pm$ 5.3	800m: 1.48,82-2.08,30
LD runners (11)	28.0 $\pm$ 4.4	179.0 $\pm$ 5.3	69.7 $\pm$ 6.1	5 km: 14.12,7-14.36,9 marathon: 2.17.58- 2.34.03
Power athletes (14)	23.5 $\pm$ 3.6	181.4 $\pm$ 5.1	77.3 $\pm$ 4.8	100m: 10.67-10.86 decathlon: 6184-7504 triple jump: 15.11
Controls (34) STUDY V	24.8 $\pm$ 3.4	178.6 $\pm$ 5.4	72.3 $\pm$ 6.8	-
400-m runners (9) STUDY VI	25.3 $\pm$ 6.4	184.1 $\pm$ 5.0	74.8 $\pm$ 4.9	400m: 48.28-52.25
Physically active (13)	24.9 $\pm$ 3.4	177.3 $\pm$ 4.1	70.7 $\pm$ 5.8	-
400-m runners (12)	26.1 $\pm$ 5.8	184.1 $\pm$ 4.6	76.8 $\pm$ 5.7	400m: 47.45-52.25

## 4.2 Protocol of maximal anaerobic running test (I - VI)

The MART consisted of a series of 20-s runs on a treadmill with a 100-s recovery between the runs. A 5-s acceleration phase was not included in the running time. The velocity of the treadmill was increased after each run until exhaustion but the slope was constant during the whole test procedure. The runs were performed at a grade of 5° (I), 4° (III - VI), 3° (female subjects) or 1°, 4° and 7° (II). Since mechanical power is difficult to measure during treadmill running the power was expressed as oxygen demand using the formula of American College of Sports Medicine (ACSM 1986). The initial oxygen demand was set to 62 ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup> (II, female subjects), 68 ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup> (I, III) or 74 ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup> (V). In study IV, the O<sub>2</sub> demand of the first run was 62 ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup> for the control and power group and 74 ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup> for the 400-m, middle and

long distance runners. In each study, the velocity of the first run as well as the increase in velocity between the runs were selected so that the blood lactate concentration would not increase over  $3 \text{ mmol} \cdot \text{l}^{-1}$  after the first run and so that exhaustion would be attained within twelve runs. The MART protocols at each grade are shown in Table 4.

TABLE 4.  $\text{O}_2$  demand and corresponding velocity of each run in the MART at the grades of  $1^\circ$ ,  $3^\circ$ ,  $4^\circ$ ,  $5^\circ$  and  $7^\circ$  calculated by the formula of the American College of Sports Medicine for inclined treadmill running (ACSM 1986).

$\text{O}_2$ demand ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	MART <sub>1</sub> ( $\text{m} \cdot \text{s}^{-1}$ )	MART <sub>3</sub> ( $\text{m} \cdot \text{s}^{-1}$ )	MART <sub>4</sub> ( $\text{m} \cdot \text{s}^{-1}$ )	MART <sub>5</sub> ( $\text{m} \cdot \text{s}^{-1}$ )	MART <sub>7</sub> ( $\text{m} \cdot \text{s}^{-1}$ )
62	4.52	3.94	3.71	3.50	3.14
68	4.98	4.35	4.09	3.86	3.46
74	5.45	4.75	4.47	4.22	3.78
80	5.91	5.16	4.85	4.57	4.11
86	6.37	5.56	5.23	4.93	4.43
92	6.84	5.97	5.61	5.29	4.75
98	7.30	6.37	5.99	5.65	5.07
104	7.77	6.78	6.37	6.01	5.39
110	8.23	7.18	6.75	6.37	5.72
116	8.69	7.59	7.13	6.73	6.04
122	9.16	7.99	7.51	7.09	6.36
128	9.62	8.40	7.89	7.44	6.68
134	10.08	8.80	8.27	7.80	7.00

In order to obtain a blood lactate vs. running velocity or power curve, fingertip blood samples were taken at rest, 40 s after each run and 2.5 and 5.0 min after exhaustion. Blood lactate concentrations were analysed by the Model 640 lactate analyser (Roche Bioelectronics, Switzerland) (I), and EBIO 6666 analyser (Eppendorf-Netheler-Hinz GmbH, Germany) (II), standard enzymatic method (Boehringer Mannheim, Germany) (III - VI) and YSI 1500 lactate analyser (Yellow Springs Inc., USA) (IV).

Before the actual tests the subjects performed three maximal counter-movement jumps ( $\text{CMJ}_{\text{rest}}$ ) on a contact mat (Newtest Co., Oulu, Finland) connected to an electronic timer. In addition, fifteen seconds as well as 2.5 and 5.0 min after exhaustion three CMJs were repeated with a 10-s interval. The height of rise of the centre of mass was determined from the flight time (Komi & Bosco 1978) as a mean of two best jumps in each case. In study I, three counter-movement jumps were also performed after each run to obtain the height of the CMJ vs. running velocity or power curve.  $\text{CMJ}_{\text{max}}$  was the highest CMJ measured after the runs or at rest.  $\text{CMJ}_{\text{decr}}$  was calculated as percentage decrease of the height of the CMJ during the MART ( $\text{CMJ}_{\text{decr}} = (\text{CMJ}_{\text{rest}} - \text{CMJ}_{\text{fatigue}}) / \text{CMJ}_{\text{rest}} \cdot 100\%$ ).  $\text{CMJ}_{\text{rest}}$  and  $\text{CMJ}_{\text{max}}$  were selected to measure force and velocity characteristics of the extensor muscles of the lower extremities and  $\text{CMJ}_{\text{decr}}$  was selected to describe muscle fatigue in the MART.

At the end of the MART, the treadmill and stopwatch were stopped when the subject could no longer run at the treadmill speed. The maximal running power ( $P_{\max}$ ) was calculated according to the ACSM formula from the velocity of the last completed 20-s run and from the exhaustion time of the following faster run. If the subject was able to complete 10 s of the last run before exhaustion his  $P_{\max}$  was calculated to be  $1 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  higher than that of the last completed run. Each additional 2 s to the exhaustion time increased the  $P_{\max}$  by  $1 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ . The maximal velocity of the MART ( $V_{\max}$ ) was also calculated so that each additional 2 s after 10 s running increased the  $V_{\max}$  by 1/6 of the total increase of the velocity between the runs. The calculation of the  $P_{\max}$  and  $V_{\max}$  was based on the relationship between power and exhaustion time in short maximal sprints on the treadmill (e.g. Margaria et al. 1971) and on our experience that a subject, who is just able to complete 20 s at a certain speed, will always be able to run at least 7 - 9 s at the next faster speed. Consequently, 10-s exhaustion time at the faster speed was chosen to represent a better performance than the power of the previous completed 20-s run.

The  $\text{O}_2$  demand associated with 3, 5 and 10  $\text{mmol} \cdot \text{l}^{-1}$  blood lactate levels ( $P_{3\text{mM}}$ ,  $P_{5\text{mM}}$  and  $P_{10\text{mM}}$ , respectively) were determined from the blood lactate vs.  $\text{O}_2$  demand curve by linear interpolation from the two consecutive blood lactate values which were above and below the desired value. The submaximal power indices of  $P_{3\text{mM}}$ ,  $P_{5\text{mM}}$  and  $P_{10\text{mM}}$  were selected since the onset of blood lactate accumulation starts at 3 - 5 mM blood lactate levels and force production of the neuromuscular system is significantly reduced at the 10 mM blood lactate concentration (Nummela et al. 1992).  $P_{[10\text{mM}-3\text{mM}]}$  was calculated by subtracting  $P_{3\text{mM}}$  from  $P_{10\text{mM}}$ . The highest blood lactate concentration after the MART (peak BLa) as well as the difference between the  $P_{\max}$  and  $\text{VO}_{2\max}$  ( $\Delta P$ ) were used as the estimates of anaerobic capacity. The use of  $\Delta P$  as an index of anaerobic capacity is based on the rationale that the work performed at an intensity of over 100% of  $\text{VO}_{2\max}$  must be anaerobic.

In order to determine the aerobic and anaerobic energy yield, oxygen uptake was measured continuously during the MARTs by Sensormedics 2900Z gas analyser (II - III).  $\text{VO}_2$  was measured every 20-s so that  $\text{VO}_2$  of each complete 20-s running bout could be determined. The accumulated  $\text{O}_2$  deficit during each complete 20-s sprint was calculated as the difference between the accumulated  $\text{O}_2$  demand and the accumulated  $\text{O}_2$  uptake.  $\text{O}_2$  deficit was calculated as a mean of all completed 20-s runs during each MART (MART<sub>1</sub>, MART<sub>4</sub> and MART<sub>7</sub>) and was expressed in  $\text{O}_2$  equivalents. The  $\text{O}_2$  deficit of the last completed 20-s run was used in the comparison of the MART and Wingate test (III). The percentages of aerobic and anaerobic contributions were calculated from the  $\text{O}_2$  uptake,  $\text{O}_2$  deficit and  $\text{O}_2$  demand values (Anaerobic% =  $\text{O}_2$  deficit /  $\text{O}_2$  demand  $\cdot$  100%; Aerobic% =  $\text{O}_2$  uptake /  $\text{O}_2$  demand  $\cdot$  100%).

### 4.3 Experimental design

The study consisted of four different measurements. (1) In order to investigate the relationships between the selected neuromuscular and metabolic variables and maximal anaerobic running performance, the subjects performed two tests on a treadmill: the MART at the slope of 5° (I), 4° (IV) or 3° (female subjects) and a maximal aerobic power test. In study I, 10 of the 13 subjects ran a maximal 400-m time trial and a maximal 20-m speed test with a running start on a track to determine their average running velocity over 400 m ( $V_{400m}$ ) and maximal running velocity ( $V_{20m}$ ), respectively. Female subjects and 48 of the 88 male subjects (IV) had their maximal running velocity measured over a 30-m section of track ( $V_{30m}$ ) in the same way as was done in the 20-m speed test. Times for the 20 m and 30 m were determined using photocells and an electronic timer (Newtest Co., Oulu, Finland). All 400-m runners performed the tests within three months of their seasonal best time in 400 m.

(2) In the second measurement, the effect of treadmill inclination on the results of the MART was investigated (II). Ten male subjects performed three MARTs at different slopes in a random order. The treadmill inclinations were 1° (MART<sub>1</sub>), 4° (MART<sub>4</sub>) and 7° (MART<sub>7</sub>). Before the MARTs the subjects ran at three intensities for 4 min to determine the submaximal steady-state oxygen uptake at corresponding grades in order to calculate the individual values of  $P_{max}$  by extrapolation of the submaximal data. Furthermore, the subjects ran a maximal 20-m speed test on a track, as described previously.

(3) In order to study the reliability and validity of the MART, the subjects performed the MART twice (III, VI) and the Wingate anaerobic test once (III). The tests were performed in a random order with at least 48 hours recovery between each test.

(4) In the study where the sprint training effects on the MART were investigated (V), the subjects performed the MART before and after the 10-week sprint training period from March to May just before the competitive season. For control purposes, the same subjects repeated the MART twice within one week in the following May a year later.

On the day preceding the tests, the subjects were advised to live normally and they were allowed to train lightly. Since the anaerobic nature of the MART, a light meal was recommended from three to four hours before the tests were started. Before the MARTs the subjects performed a warm-up during which counter-movement jumps and treadmill running were practised.

### 4.4 Aerobic power and oxygen demand determination (I-II, IV)

Female subjects and male subjects in study I performed the incremental maximal aerobic power test 2 h after the MART but in study IV the aerobic power test was performed on a separate day. The initial velocity and the slope



of the treadmill were  $1.75 \text{ m} \cdot \text{s}^{-1}$  and  $1^\circ$ , respectively. The velocity of the treadmill was increased by  $0.50 \text{ m} \cdot \text{s}^{-1}$  after every 3 min until exhaustion. The oxygen uptake ( $\text{VO}_2$ ) was measured by Oxygon IV gas analyser (Mijnhardt, The Netherlands) during the whole test and blood samples were taken from the fingertip every 3 min to measure blood lactate concentrations. The blood lactate concentration was analysed by a commercial enzymatic test kit (Boehringer Mannheim, Germany). The purpose of the aerobic power test was to determine maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ) as a mean of the two highest 30-s values and anaerobic threshold ( $\text{Th}_{\text{an}}$ ) (Aunola & Rusko 1984).

In study II, running velocity of the submaximal runs was determined by using the formula of the American College of Sports Medicine for inclined treadmill running (ACSM 1986):

$$\text{VO}_2 (\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = 12 \cdot v (\text{m} \cdot \text{s}^{-1}) + 54 \cdot \text{grade (frac)} \cdot v (\text{m} \cdot \text{s}^{-1}) + 3.5,$$

where  $v$  equals the velocity of the treadmill, grade equals the slope of the treadmill expressed as the tangent of the angle with the horizontal, and 3.5 is the oxygen uptake at rest ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ). Running velocities during the three 4-min runs at each grade corresponded to the  $\text{O}_2$  demands of 40, 45 and  $50 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ . Thus, the initial velocities were  $2.82$ ,  $2.31$  and  $1.96 \text{ m} \cdot \text{s}^{-1}$  at the inclinations of  $1^\circ$ ,  $4^\circ$  and  $7^\circ$ , respectively. Fingertip blood samples were taken after each run to determine blood lactate concentration (EBIO 6666, Eppendorf-Netheler-Hinz GmbH, Germany). The average  $\text{VO}_2$  during the last minute of the submaximal runs was used as steady-state  $\text{VO}_2$ . Oxygen uptake was measured every 20-s during the runs by Sensormedics 2900Z gas analyser. At each grade, the individual linear relationship between running velocity and  $\text{VO}_2$  of the MART and corresponding  $\text{O}_2$  demand was determined. The  $\text{O}_2$  demand was assumed to increase linearly for each subject from the constant Y-intercept of  $5 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  through the near maximal  $\text{O}_2$  uptake (Medbø et al. 1988).

#### 4.5 Protocol of Wingate test (III)

A Monark ergometer and sensor optical system connected to the computer programme (SMI Power Version 1.02, St. Cloud, USA) were used to perform the Wingate anaerobic test. The precision of the sensor in measuring revolutions per minute (rpm) as a function of 16 markers and a flywheel speed of 400 rpm was  $\pm 0.5\%$ . After a 5-min warm up and one minute rest a fingertip blood sample was taken to determine the resting blood lactate concentration. The load was set to  $0.0872 \text{ kp} \cdot \text{kg}^{-1}$ , which equals  $5.13 \text{ J} \cdot \text{rev}^{-1} \cdot \text{kg}^{-1}$  (Dotan & Bar-Or 1983, Patton et al. 1985). A flying start was used so that the acceleration phase (3 s) was not used in the calculations. In order to determine the blood lactate concentrations, fingertip blood samples were taken 40 s, 2.5 min, 5 min and 10 min after the test. Blood lactate concentrations were analysed by a standard enzymatic method (Boehringer Mannheim, Germany).

The SMI Power Version 1.02 was used to calculate three indices: peak power, the highest power ( $\text{W} \cdot \text{kg}^{-1}$ ) during a 5-s period; total work, work ( $\text{J} \cdot$

kg<sup>-1</sup>) performed during the 30-s period; and fatigue index, percentage decrease of power from the highest 5-s power output to the lowest 5-s power output. Oxygen demand was calculated by the ACSM formula for leg ergometer (ACSM 1986):

$$\text{VO}_2 (\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = \text{load (kg)} \cdot 6 \cdot n (\text{rev} \cdot \text{min}^{-1}) \cdot 2 \cdot \text{BM}^{-1} (\text{kg}) + 3.5,$$

where load = frictional load of the ergometer; 6 = one revolution in Monark ergometer (m · rev<sup>-1</sup>); n = revolutions per minute; BM = body mass; and 3.5 = oxygen uptake at rest (ml · kg<sup>-1</sup> · min<sup>-1</sup>). Oxygen uptake was measured breath by breath (Sensormedics 2900Z gas analyser) one minute before the test and during the whole test. Oxygen deficit and anaerobic contributions were calculated likewise in the MART.

To evaluate the validity of the MART, the corresponding variables of the MART and Wingate test were compared. The following variables, which were thought to measure similar qualities, were chosen for comparison: P<sub>max</sub> (MART) and total work (Wingate) reflect muscles' ability to sustain extremely high power; CMJ<sub>rest</sub> (MART) and peak power (Wingate) are reflections of the ability of the limb muscles to produce high mechanical power in a short time; the CMJ<sub>decr</sub> (MART) and fatigue index (Wingate), which are measures for the degree of power drop-off during the tests; peak blood lactate in both tests is an indirect indication of the lactic anaerobic capacity; oxygen deficit in both tests is the measure of the amount of energy drawn by the working muscles from sources other than the oxygen uptake through the mouth; and finally, the percentage anaerobic contribution in both tests is a general indication for the energy sources of the tests.

## 4.6 Sprint training (V)

Running exercises were divided into three different categories (Table 5) according to the intensity and the distance of the runs. Speed training consisted of short sprints (20 m - 80 m) at high velocity (> 95% of the maximum velocity) aiming to increase maximal running speed. Intensive interval training included runs from 60 m to 600 m at the velocity of 80% - 95% of the maximum velocities of selected distances. Short intensive intervals (< 100 m) were expected to improve alactic speed endurance and long intervals (100 m - 600 m) lactic speed endurance. Extensive interval training included intervals from 100 m to 600 m at velocity below 80% of the maximum velocity of selected distances and was intended to improve mixed aerobic and anaerobic performance characteristics. Strength training included weight lifting series and repetitions such as 2 - 4 × 1 - 10 × 50% - 100% of one repetition maximum. Bounding exercises included vertical and horizontal jumps such as plyometrics, hopping and jumping exercises. The intensity of the strength and bounding exercises was aimed to be 90% - 100% of the best performance during the whole training period. Furthermore, general endurance training included warm-up runs and aerobic

runs at a constant velocity ( $< 4.0 \text{ m} \cdot \text{s}^{-1}$ ) during the training period ( $21.6 \pm 22.2 \text{ km} \cdot \text{week}^{-1}$ ).

The athletes' training was supervised by their personal coaches and the research group. The training data of the athletes were analysed from their training diaries. General trends in the training of each athlete were similar but great individual differences were observed in the training volume (Table 5). The intensity of exercises increased and the volume of exercises decreased towards the end of the 10-week training period while the total number of exercises per week remained unchanged. During the training period the sprinters' main focus was on maximising their anaerobic performance characteristics and minor emphasis was placed on their aerobic systems and muscle strength. On the average, the sprinters trained  $6.3 \pm 1.9$  times per week during the 10-week training period. The relative contribution of extensive and intensive intervals were  $12.9 \pm 7.2\%$  and  $16.3 \pm 5.0\%$  of the total number of training sessions, respectively. The corresponding contributions of speed training, bounding exercises and strength training were  $12.9 \pm 7.3\%$ ,  $10.1 \pm 6.5\%$  and  $19.3 \pm 16.1\%$ , respectively.

#### 4.7 Statistical methods

All statistical comparisons and analysis were done by the SPSS/PC+™ programme (SPSS Inc., USA). Standard statistical methods were used to calculate mean, standard deviation (SD), standard error of estimate (SE) and Pearson's correlation coefficient. The changes in CMJ and blood lactate concentration during the MART were tested using an analysis of variance for repeated measures (I). The reproducibility of the MART was evaluated by correlation coefficients and by the test of Bland & Altman (1986) (III, VI). In addition, standard error of estimate and coefficients of variation were used for reliability purposes. The differences between the two MARTs and the influence of the group on the reproducibility was tested for significance by employing a multiple analysis of variance (MANOVA) for repeated measures. To evaluate the validity of the MART, the results of the second trial of the test were compared with the corresponding variables of the Wingate test using correlation analysis (III).

The differences between the results of the three MART protocols at different treadmill inclinations were tested for significance employing the MANOVA (II). The changes in  $\text{VO}_2$  and  $\text{O}_2$  deficit during the MART at each grade were tested by the analysis of variance for repeated measures. In order to show the dependency of  $P_{\text{max}}$  on the neuromuscular and metabolic factors at each grade, the relationships between the  $P_{\text{max}}$  and other test variables were tested using the correlation analysis.

The results of the MART in different groups were compared using a one-way analysis of variance and the Scheffe post hoc test (IV). The data were also entered into a forward inclusion and backward elimination linear regression analysis to select the variables that best predicted the average velocity of 400-m

run and  $P_{\max}$  (IV). A variable removal criteria available in SPSS/PC+™ was at  $P < 0.10$  level.

The MANOVA was also used to evaluate the response to sprint training (V). The significance of changes between the pre- and post-test results of the MART and differences between the experimental and control groups (groups by training interaction) were indicated by MANOVA. In addition, correlation analysis was used to evaluate the effect of different training methods on the variables of the MART.

TABLE 5. Average training data and description of various training methods during the 10-week intensive sprint training period. Values are expressed as a mean  $\pm$  standard deviation. Training volume and number of training sessions correspond to the total amount for the 10 week period.

	Training volume	Number of training sessions	Running velocity ( $\text{m} \cdot \text{s}^{-1}$ )		% of best performance	Rest in reps / sets (min)	Objective of training
			runs <150m	runs >150m			
Speed training	2.8 $\pm$ 2.4 <sup>a</sup>	9.0 $\pm$ 5.2	9.0 - 9.5	-	>95	3-5 / 6-8	speed and anaerobic power
Intensive interval training	17.5 $\pm$ 13.8 <sup>a</sup>	13.8 $\pm$ 9.1	6.5 - 8.9	6.0 - 8.5	80 - 95	1-6 / 3-10	anaerobic power and capacity
Extensive interval training	20.1 $\pm$ 11.4 <sup>a</sup>	10.1 $\pm$ 5.5	5.0 - 6.4	4.0 - 5.9	50 - 79	0.5-1.5 / 2-3	aerobic/anaerobic metabolism
Endurance training	216 $\pm$ 222 <sup>a</sup>	26.9 $\pm$ 21.7	-	<4.0	<50	-	aerobic metabolism
Bounding exercises	1180 $\pm$ 887 <sup>b</sup>	7.8 $\pm$ 5.7	-	-	80 - 100	1-3 / 4-6	muscle power
Strength training	59.4 $\pm$ 34.0 <sup>c</sup>	12.0 $\pm$ 6.7	-	-	50 - 100	1-3 / 4-6	muscle strength

a = km; b = jump contacts; c = tons

## 5 RESULTS

### 5.1 Determinants of maximal anaerobic running performance (I, IV)

The 400-m runners had higher  $P_{\max}$  in the MART<sub>4</sub> than the power athletes, long distance runners and control group ( $P < 0.01$ ) but no significant difference was observed between the 400-m and middle distance runners (Table 6). The 400-m runners also had higher  $P_{10mM}$  than the power athletes, long distance runners and control group ( $P < 0.001$ ) but they did not differ significantly from the middle distance runners. The long distance runners had the lowest peak BLa and  $\Delta P$  ( $P < 0.01$ ). Peak BLa did not differ between the power athletes, 400-m and middle distance runners, although the 400-m runners had greater  $\Delta P$  than the middle distance runners. The power athletes and 400-m runners had significantly higher  $CMJ_{\text{rest}}$  than the other groups ( $P < 0.001$ ).

The correlation analyses between the variables of the MART<sub>5</sub>, 20-m speed test, aerobic power test and 400-m time trial for the homogeneous group of 400-m runners are shown in Figure 1. A positive correlation was observed between the  $P_{\max}$  and the average velocity in the 400-m run. Correlation analyses also revealed that  $P_{10mM}$  and  $V_{20m}$  were the most important determinants of the  $P_{\max}$  and  $V_{400m}$ . Moreover, peak BLa correlated positively with the  $V_{400m}$ .

Similar results were obtained when the results of the MART<sub>4</sub> were employed in the regression and correlation analyses (Figure 2). The difference between the MART<sub>4</sub> and MART<sub>5</sub> was that the slope of the treadmill was 4° and 5°, respectively, and CMJs were performed after each run in the MART<sub>5</sub> but only before and after the MART<sub>4</sub>.

TABLE 6. MART<sub>4</sub> results in various groups. Abbreviations: MD = middle distance; LD = long distance; P<sub>max</sub> = maximal power; P<sub>10mM</sub> = power at 10 mmol · l<sup>-1</sup> blood lactate level; P<sub>5mM</sub> = power at 5 mmol · l<sup>-1</sup> blood lactate level; Peak BL<sub>a</sub> = peak blood lactate concentration; CMJ<sub>rest</sub> = height of counter-movement jump at rest; CMJ<sub>decr</sub> = relative decrease of counter-movement jump in the MART<sub>4</sub>; ΔP = difference between P<sub>max</sub> and maximal oxygen uptake; VO<sub>2max</sub> = maximal oxygen uptake; V<sub>30m</sub> = average velocity during a 30-m speed test with a running start.

	Power (n=14)	400m runners (n=21)	MD runners (n=8)	LD runners (n=11)	Control (n=34)	ANOVA
P <sub>max</sub> (ml · kg <sup>-1</sup> · min <sup>-1</sup> )	117.8 ± 4.1	125.0 ± 4.1	120.7 ± 6.2	108.4 ± 4.1	108.0 ± 6.2	P < 0.001 <sup>a</sup>
P <sub>10mM</sub> (ml · kg <sup>-1</sup> · min <sup>-1</sup> ) <sup>j</sup>	108.2 ± 5.7	118.0 ± 4.2	116.1 ± 6.0	107.1 ± 4.7	103.2 ± 5.9	P < 0.001 <sup>b</sup>
P <sub>5mM</sub> (ml · kg <sup>-1</sup> · min <sup>-1</sup> )	90.1 ± 6.5	100.5 ± 6.6	102.5 ± 7.4	97.6 ± 5.9	90.0 ± 7.4	P < 0.001 <sup>c</sup>
Peak BL <sub>a</sub> (mmol · l <sup>-1</sup> )	17.1 ± 1.8	17.1 ± 3.3	15.8 ± 2.7	9.9 ± 1.8	14.2 ± 2.7	P < 0.001 <sup>d</sup>
CMJ <sub>rest</sub> (cm)	50.9 ± 5.0	50.0 ± 5.8	39.1 ± 4.1	35.3 ± 5.3	40.9 ± 5.4	P < 0.001 <sup>e</sup>
CMJ <sub>decr</sub> (%)	16.0 ± 4.3	17.4 ± 6.6	11.5 ± 4.4	4.2 ± 4.6	13.6 ± 6.9	P < 0.001 <sup>f</sup>
ΔP (ml · kg <sup>-1</sup> · min <sup>-1</sup> ) <sup>k</sup>	-	64.2 ± 6.3	52.9 ± 7.3	36.3 ± 4.5	50.1 ± 6.0	P < 0.001 <sup>g</sup>
VO <sub>2max</sub> (ml · kg <sup>-1</sup> · min <sup>-1</sup> ) <sup>k</sup>	-	61.4 ± 6.3	66.5 ± 4.8	72.1 ± 3.3	57.9 ± 10.2	P < 0.001 <sup>h</sup>
V <sub>30m</sub> (m · s <sup>-1</sup> ) <sup>l</sup>	-	9.97 ± 0.50	9.08 ± 0.38	8.27 ± 0.33	8.53 ± 0.43	P < 0.001 <sup>i</sup>

a = Power, 400m and Middle Distance > Long Distance and Control; 400m > Power; b = 400m and Middle Distance > Power, Long Distance and Control; c = 400m and Middle Distance > Power and Control; Long Distance > Control; d = Power, 400m, Middle Distance and Control > Long Distance; 400m and Power > Control; e = Power and 400m > Middle and Long Distance and Control; f = Power, 400m and Control > Long Distance; g = Power, 400m, Middle Distance and Control > Long Distance; 400m > Control and Middle Distance; h = Long Distance > 400m and Control; i = 400m > Middle and Long Distance and Control (P < 0.05); j = Long Distance (n = 8); k = 400m (n = 18), Middle Distance (n = 6), Long Distance (n = 9), Control (n = 11); l = 400m (n = 19), Middle Distance (n = 3), Long Distance (n = 5), Control (n = 18).

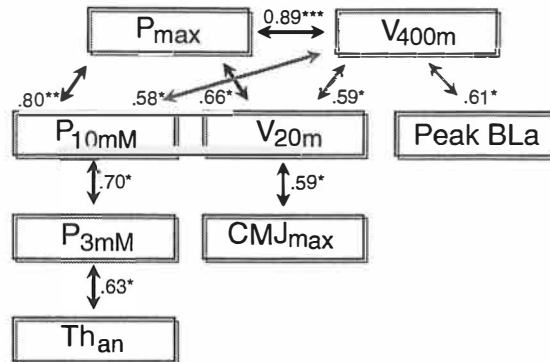


FIGURE 1. Correlation analyses between the variables of the MART<sub>5</sub>, aerobic power test, 20-m speed test and 400-m time trial for the homogeneous group of 400-m runners ( $n = 13$ ). The 400-m time trial was performed by ten sprinters. Abbreviations:  $P_{max}$  = maximal power;  $P_{10mM}$  = power at  $10\text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $P_{3mM}$  = power at  $3\text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $V_{400m}$  = average velocity in the 400-m time trial;  $V_{20m}$  = average velocity in the 20-m speed test;  $CMJ_{max}$  = the highest counter-movement jump during the MART;  $Peak\ BL_a$  = peak blood lactate concentration;  $Th_{an}$  = oxygen demand at anaerobic threshold.

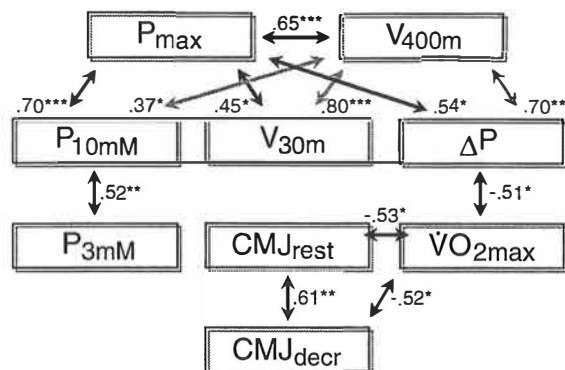


FIGURE 2. Correlation analyses between the variables of the MART<sub>4</sub>, aerobic power test, 30-m speed test and 400-m race for the homogeneous group of 400-m runners ( $n = 17$ ). Abbreviations:  $P_{max}$  = maximal power;  $P_{10mM}$  = power at  $10\text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $P_{3mM}$  = power at  $3\text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $CMJ_{rest}$  = height of counter-movement jump at rest;  $CMJ_{decr}$  = percentage decrease of the counter-movement jump in the MART;  $V_{400m}$  = average velocity in the 400-m race;  $V_{30m}$  = average velocity in the 30-m speed test;  $\Delta P$  = difference between the  $P_{max}$  and  $VO_{2max}$ ;  $VO_{2max}$  = maximal oxygen uptake.



Stepwise regression analysis revealed that the  $V_{30m}$ ,  $P_{10mM}$  and  $\Delta P$  accounted for 87% of the total variation in the average velocity of the 400-m run ( $V_{400m}$ ), and the  $V_{30m}$ ,  $P_{10mM}$  and peak BLa accounted for 92% ( $P < 0.001$ ) of the variation in the  $P_{max}$  of the MART<sub>4</sub>. The linear regression equations for the  $V_{400m}$  and  $P_{max}$  were:

$$V_{400m} = 0.538 \cdot [V_{30m}] + 0.017 \cdot [P_{10mM}] + 0.014 \cdot [\Delta P] \text{ and}$$

$$P_{max} = 0.736 \cdot [P_{10mM}] + 2.473 \cdot [V_{30m}] + 0.815 \cdot [\text{peak BLa}].$$

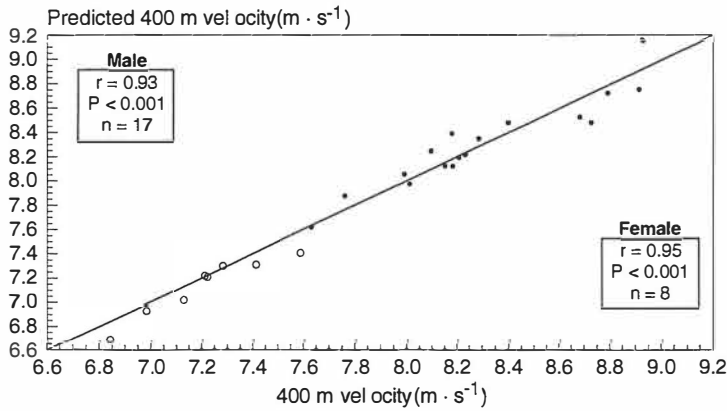


FIGURE 3. Relationship between predicted and actual 400-m running velocity in 17 male (MART<sub>4</sub>, dots) and 8 female (MART<sub>3</sub>, circles) 400-m runners. Line corresponds to identity line.

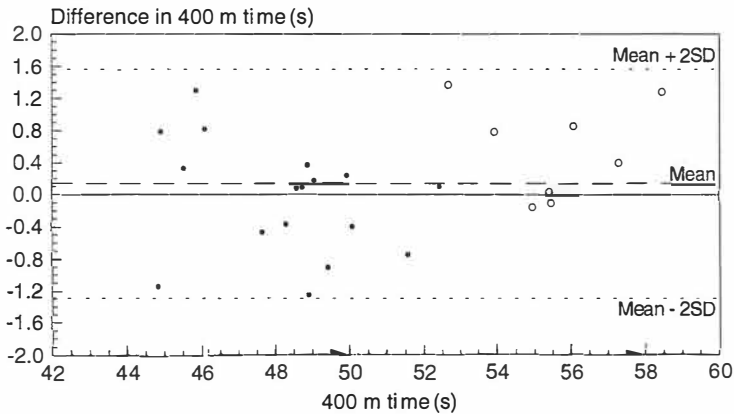


FIGURE 4. Difference between predicted and actual 400-m race time in 17 male (dots) and 8 female (circles) 400-m runners.

The 95% confidence interval for the bias was  $\pm 0.43$  s for 400-m race time and  $\pm 0.75$  ml  $\cdot$  kg $^{-1}$   $\cdot$  min $^{-1}$  for  $P_{\max}$ . The validity of the regression equation for the  $V_{400m}$  was tested on female runners who performed the MART at the inclination of 3°. The correlation coefficient between the predicted and actual 400-m running velocity was 0.95, which was equal to that of the male subjects ( $r = 0.93$ ). The accuracy of the regression equation of the  $V_{400m}$  is shown in Figures 3 and 4.

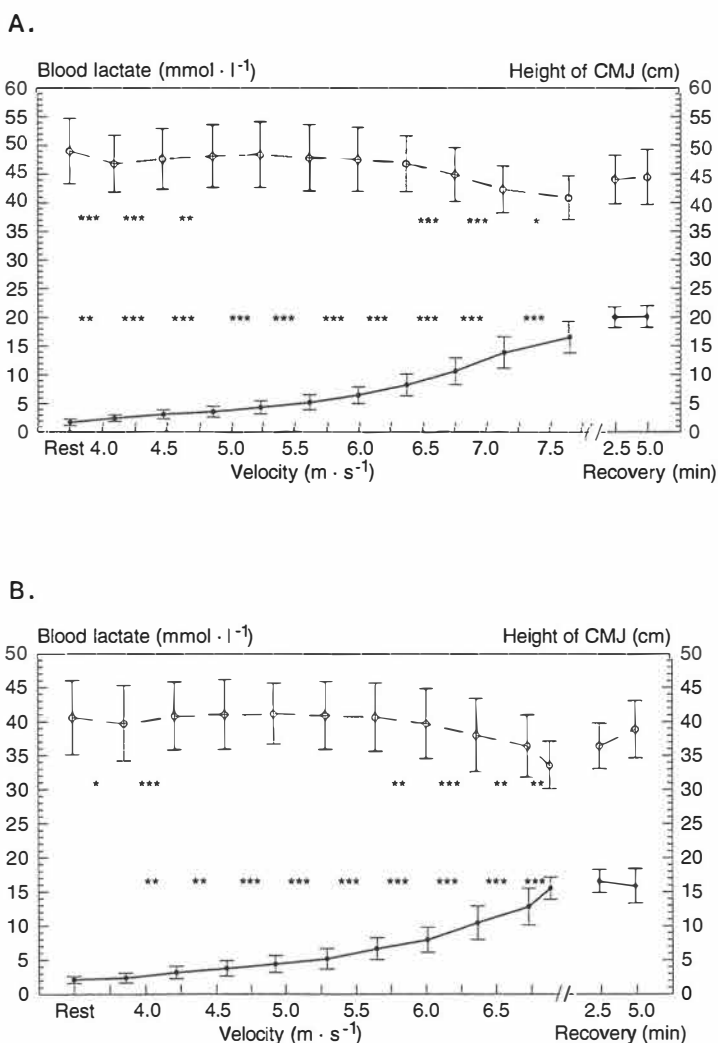


FIGURE 5. Blood lactate concentration (solid line) and the height of the counter-movement jump (dashed line) during the MART<sub>4</sub> (5a) and MART<sub>5</sub> (5b) as well as during a 5-min recovery period. The differences between two consecutive values in the counter-movement jump and blood lactate were tested by the analysis of variance for repeated measures. (\*  $P < 0.05$ ; \*\*  $P < 0.01$ ; \*\*\*  $P < 0.001$ )

The highest CMJ was attained at rest in the MART<sub>4</sub> and after the fourth run in the MART<sub>5</sub> (Figure 5). The height of the CMJ decreased significantly after the eighth run in the MART<sub>4</sub> and after the seventh run in the MART<sub>5</sub> when the blood lactate concentrations were  $10.6 \pm 2.3 \text{ mmol} \cdot \text{l}^{-1}$  and  $8.0 \pm 1.9 \text{ mmol} \cdot \text{l}^{-1}$ , respectively.

## 5.2 Effects of treadmill inclination (II)

The  $V_{\text{max}}$  of the MART<sub>1</sub>, MART<sub>4</sub> and MART<sub>7</sub> for physically active men were  $7.48 \pm 0.36 \text{ m} \cdot \text{s}^{-1}$ ,  $6.66 \pm 0.40 \text{ m} \cdot \text{s}^{-1}$  and  $5.79 \pm 0.27 \text{ m} \cdot \text{s}^{-1}$ , respectively. Individually calculated  $P_{\text{max}}$  increased from  $94.1 \pm 8.8$  and  $110.0 \pm 10.2$  to  $119.5 \pm 8.0 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  when the grade of uphill running increased from  $1^\circ$  and  $4^\circ$  to  $7^\circ$ , respectively ( $P < 0.001$ ; Table 7). When using the ACSM formula the respective  $P_{\text{max}}$  values were  $100.3 \pm 4.7$ ,  $108.5 \pm 6.3$  and  $111.3 \pm 5.0 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ .  $P_{10\text{mM}}$  and  $P_{5\text{mM}}$  were lower at the grade of  $1^\circ$  than at  $4^\circ$  and  $7^\circ$  ( $P < 0.001$ ). The peak BLA was higher in the MART<sub>7</sub> than in the MART<sub>1</sub> and MART<sub>4</sub> ( $P < 0.01$ ).

TABLE 7. Average ( $\pm$ SD) values in the MART<sub>1</sub>, MART<sub>4</sub> and MART<sub>7</sub>. MANOVA indicated the difference between the tests ( $n = 10$ ). The  $P_{\text{max}}$  as well as  $P_{10\text{mM}}$  and  $P_{5\text{mM}}$  were individually calculated from submaximal oxygen demand values. Abbreviations:  $P_{\text{max}}$  = maximal power;  $P_{10\text{mM}}$  = power at  $10 \text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $P_{5\text{mM}}$  = power at  $5 \text{ mmol} \cdot \text{l}^{-1}$  blood lactate level; Peak BLA = peak blood lactate concentration;  $\text{CMJ}_{\text{rest}}$  = height of counter-movement jump at rest;  $\text{CMJ}_{\text{decr}}$  = relative decrease of the counter-movement jump in the MART.

	MART <sub>1</sub>	MART <sub>4</sub>	MART <sub>7</sub>	MANOVA
$P_{\text{max}}$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	$94.1 \pm 8.8$	$110.0 \pm 10.2$	$119.5 \pm 8.0$	$P < 0.001^a$
$P_{10\text{mM}}$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	$93.5 \pm 8.5$	$108.7 \pm 8.6$	$113.7 \pm 8.6$	$P < 0.001^b$
$P_{5\text{mM}}$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	$83.6 \pm 7.2$	$94.9 \pm 6.4$	$95.0 \pm 9.9$	$P < 0.001^b$
Peak BLA ( $\text{mmol} \cdot \text{l}^{-1}$ )	$12.0 \pm 2.2$	$13.0 \pm 3.0$	$15.4 \pm 2.8$	$P = 0.002^c$
$\text{CMJ}_{\text{rest}}$ (cm)	$42.0 \pm 4.3$	$40.7 \pm 4.5$	$41.8 \pm 3.7$	$P = 0.239$
$\text{CMJ}_{\text{decr}}$ (%)	$12.1 \pm 4.4$	$11.0 \pm 5.2$	$15.5 \pm 5.8$	$P = 0.256$

a =  $1^\circ$  vs.  $4^\circ$ ,  $7^\circ$  and  $4^\circ$  vs.  $7^\circ$  ( $P < 0.05$ ); b =  $1^\circ$  vs.  $4^\circ$ ,  $7^\circ$  ( $P < 0.05$ ); c =  $7^\circ$  vs.  $1^\circ$ ,  $4^\circ$  ( $P < 0.05$ )

The correlation analysis showed that all MART variables correlated positively with the  $P_{\text{max}}$  in the MART<sub>4</sub>, while only  $P_{10\text{mM}}$  and  $\text{CMJ}_{\text{rest}}$  correlated positively with the  $P_{\text{max}}$  in the MART<sub>7</sub> (Table 8). Furthermore, the correlation coefficients between the  $P_{\text{max}}$ ,  $P_{10\text{mM}}$  and  $P_{5\text{mM}}$  in the three different MART protocols were higher between the MART<sub>1</sub> and MART<sub>4</sub> than between the MART<sub>1</sub> and MART<sub>7</sub> (Table 9).

TABLE 8. Correlation matrix between the  $P_{\max}$  and selected variables of the MART<sub>1</sub>, MART<sub>4</sub> and MART<sub>7</sub> and 20-m speed test (n = 10). Abbreviations:  $P_{\max}$  = maximal power;  $P_{10\text{mM}}$  = power at 10 mmol · l<sup>-1</sup> blood lactate level;  $P_{5\text{mM}}$  = power at 5 mmol · l<sup>-1</sup> blood lactate level; Peak BL<sub>a</sub> = peak blood lactate concentration; CMJ<sub>rest</sub> = height of counter-movement jump at rest; CMJ<sub>decr</sub> = relative decrease of the counter-movement jump in the MART;  $V_{20\text{m}}$  = average velocity in the 20-m speed test.

	$P_{\max}$		
	MART <sub>1</sub>	MART <sub>4</sub>	MART <sub>7</sub>
$P_{10\text{mM}}$ (ml · kg <sup>-1</sup> · min <sup>-1</sup> )	0.99***	0.97***	0.83**
$P_{5\text{mM}}$ (ml · kg <sup>-1</sup> · min <sup>-1</sup> )	0.65*	0.66*	0.52
Peak BL <sub>a</sub> (mmol · l <sup>-1</sup> )	0.54	0.83***	0.39
CMJ <sub>rest</sub> (cm)	0.77**	0.75**	0.62*
CMJ <sub>decr</sub> (%)	0.29	0.60*	0.26
$V_{20\text{m}}$ (m · s <sup>-1</sup> )	0.69*	0.59*	0.42

\*\*\* P < 0.001; \*\* P < 0.01; \* P < 0.05

TABLE 9. Correlation analyses between the  $P_{\max}$ ,  $P_{10\text{mM}}$ ,  $P_{5\text{mM}}$  and peak BL<sub>a</sub> of three different MART protocols (n = 10). Abbreviations: MART<sub>1</sub> = MART at the grade of 1°; MART<sub>4</sub> = MART at the grade of 4°; MART<sub>7</sub> = MART at the grade of 7°;  $P_{\max}$  = maximal power;  $P_{10\text{mM}}$  = power at 10 mmol · l<sup>-1</sup> blood lactate level;  $P_{5\text{mM}}$  = power at 5 mmol · l<sup>-1</sup> blood lactate level; Peak BL<sub>a</sub> = peak blood lactate concentration.

		MART <sub>4</sub>	MART <sub>7</sub>
$P_{\max}$	MART <sub>1</sub>	0.93***	0.65*
	MART <sub>4</sub>		0.64*
$P_{10\text{mM}}$	MART <sub>1</sub>	0.90***	0.18
	MART <sub>4</sub>		0.26
$P_{5\text{mM}}$	MART <sub>1</sub>	0.75**	0.43
	MART <sub>4</sub>		0.35
Peak BL <sub>a</sub>	MART <sub>1</sub>	0.56*	0.58*
	MART <sub>4</sub>		0.82**

\*\*\* P < 0.001; \*\* P < 0.01; \* P < 0.05

TABLE 10. Multiple regression analyses for the selected variables and the  $P_{\max}$  of the MART at different slopes of the treadmill (n = 10). Abbreviations: MART<sub>1</sub> = MART at the grade of 1°; MART<sub>4</sub> = MART at the grade of 4°; MART<sub>7</sub> = MART at the grade of 7°;  $P_{10\text{mM}}$  = power at 10 mmol · l<sup>-1</sup> blood lactate level; Peak BL<sub>a</sub> = peak blood lactate concentration;  $V_{20\text{m}}$  = average velocity in the 20-m speed test.

	MART <sub>1</sub>		MART <sub>4</sub>		MART <sub>7</sub>	
	Multiple R <sup>2</sup>	Partial R <sup>2</sup>	Multiple R <sup>2</sup>	Partial R <sup>2</sup>	Multiple R <sup>2</sup>	Partial R <sup>2</sup>
$P_{10\text{mM}}$	0.98***	0.98***	0.95***	0.95***	0.69***	0.69***
Peak BL <sub>a</sub>	0.99	0.01	0.99**	0.04**	0.94**	0.25**
$V_{20\text{m}}$	0.99	0.00	1.00*	0.01*	0.95	0.01

\*\*\* P < 0.001; \*\* P < 0.01; \* P < 0.05

Stepwise regression analysis revealed that  $P_{10mM}$  accounted for 97.9% of the variation in the  $P_{max}$  of the  $MART_1$  (Table 10).  $P_{10mM}$ , peak BLa and  $V_{20m}$  accounted for 99.5% and  $P_{10mM}$  and peak BLa accounted for 93.9% of the variation in the  $P_{max}$  of the  $MART_4$  and  $MART_7$ , respectively.

### 5.3 Anaerobic and aerobic energy yield during MART (II)

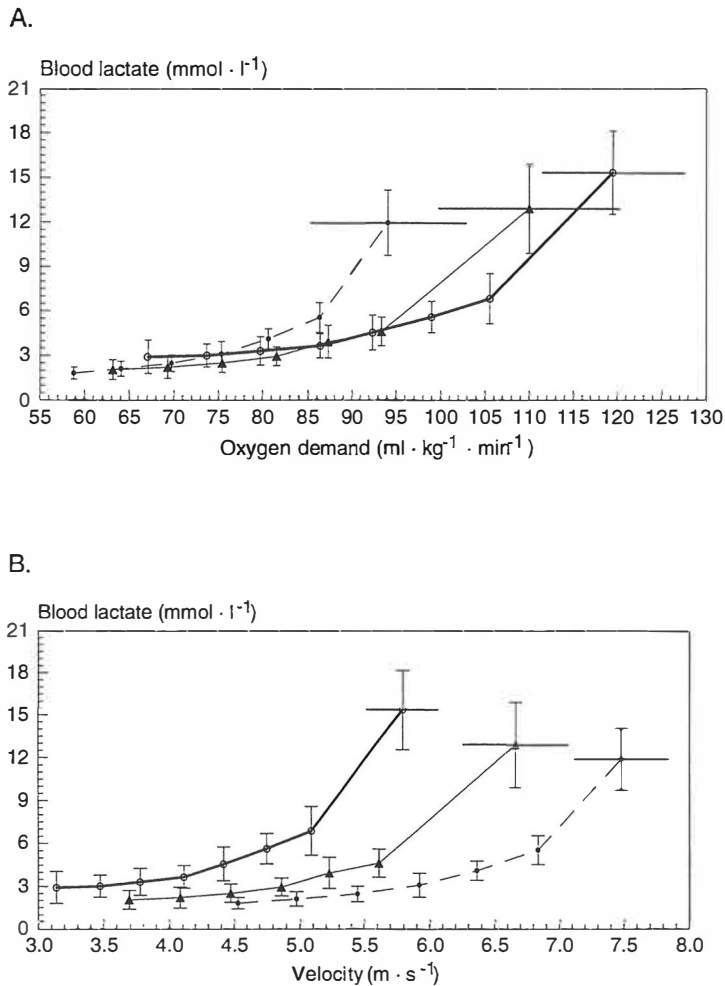


FIGURE 6. Blood lactate vs. oxygen demand (a) and running velocity (b) curves of the  $MART_1$  (dashed lines),  $MART_4$  (solid thin lines) and  $MART_7$  (solid thick lines) ( $n = 10$ ). Although all runs should have also horizontal standard deviation bars in figure 6a, the bars were marked only in the last runs at each grade to avoid unclear presentation.

Blood lactate vs.  $O_2$  demand as well as blood lactate vs. running velocity curves in the MART<sub>1</sub>, MART<sub>4</sub> and MART<sub>7</sub> are shown in Figure 6. The  $VO_2$  and  $O_2$  deficit increased with velocity during each MART ( $P < 0.01$ ; Figure 7 and 8). The average  $VO_2$  was similar between the tests but the average  $O_2$  deficit increased from  $15.3 \pm 1.2 \text{ ml} \cdot \text{kg}^{-1}$  (MART<sub>1</sub>) to  $17.3 \pm 1.3 \text{ ml} \cdot \text{kg}^{-1}$  (MART<sub>4</sub>) and  $19.6 \pm 1.3 \text{ ml} \cdot \text{kg}^{-1}$  (MART<sub>7</sub>) ( $P < 0.05$ ). Consequently, the average contribution of anaerobic energy yield was  $63.6 \pm 3.4\%$ ,  $66.1 \pm 4.4\%$  and  $68.3 \pm 4.0\%$  in the MART<sub>1</sub>, MART<sub>4</sub> and MART<sub>7</sub>, respectively.

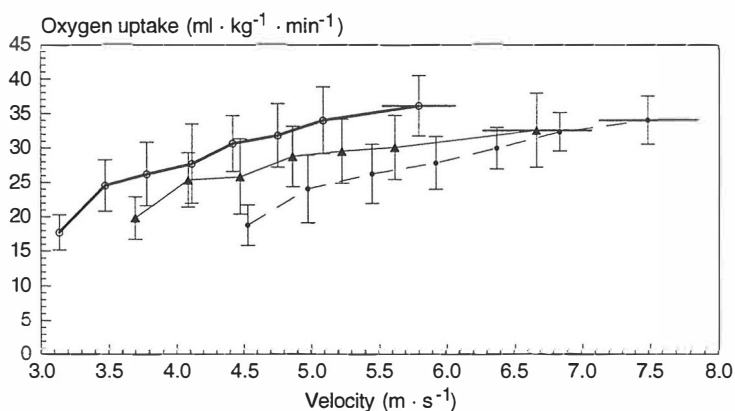


FIGURE 7. Oxygen uptake vs. running velocity curves of the MART<sub>1</sub> (dashed lines), MART<sub>4</sub> (solid thin lines) and MART<sub>7</sub> (solid thick lines) ( $n = 10$ ).

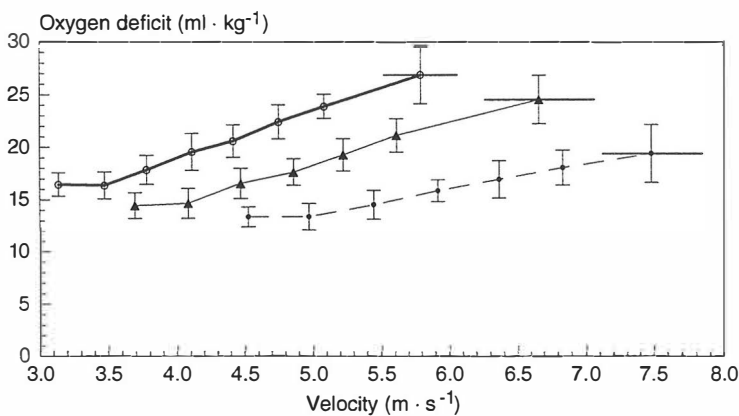


FIGURE 8. Oxygen deficit vs. running velocity curves of the MART<sub>1</sub> (dashed lines), MART<sub>4</sub> (solid thin lines) and MART<sub>7</sub> (solid thick lines) ( $n = 10$ ).

## 5.4 Comparison between MART and Wingate test (III)

The results of the MART<sub>4</sub> and Wingate test are shown in Table 11. The contribution of anaerobic energy yield was higher in the Wingate test than during the last complete 20-s run of the MART<sub>4</sub> ( $P < 0.001$ ). However, non-significant differences were observed in the peak BLa. The correlations between the corresponding variables of the MART<sub>4</sub> and Wingate test are shown in Table 12. Although four out of seven of the correlations were significant they were not high ( $0.52 < r < 0.59$ ).

TABLE 11. Results of MART<sub>4</sub> and Wingate test ( $n = 13$ ). Abbreviations:  $P_{\max}$  = maximal power;  $P_{10\text{mM}}$  = power at  $10 \text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $P_{5\text{mM}}$  = power at  $5 \text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $\text{CMJ}_{\text{rest}}$  = height of counter-movement jump at rest;  $\text{CMJ}_{\text{decr}}$  = percentage decrease of CMJ in the MART; Peak BLa = peak blood lactate concentration;  $\text{O}_2$  deficit = oxygen deficit; Anaerobic% = contribution of anaerobic energy yield.

MART <sub>4</sub>	Mean $\pm$ SD	Wingate test	Mean $\pm$ SD
$P_{\max}$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	$111 \pm 5$	Total work ( $\text{J} \cdot \text{kg}^{-1}$ )	$304 \pm 29$
$P_{10\text{mM}}$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) <sup>a</sup>	$106 \pm 5$		
$P_{5\text{mM}}$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	$89 \pm 9$		
$\text{CMJ}_{\text{rest}}$ (cm)	$43.2 \pm 5.8$	Peak power ( $\text{W} \cdot \text{kg}^{-1}$ )	$12.2 \pm 1.3$
$\text{CMJ}_{\text{decr}}$ (%)	$10.8 \pm 3.8$	Fatigue index (%)	$33.2 \pm 10.6$
Peak BLa ( $\text{mmol} \cdot \text{l}^{-1}$ )	$14.1 \pm 2.0$	Peak BLa ( $\text{mmol} \cdot \text{l}^{-1}$ )	$13.2 \pm 2.4$
$\text{O}_2$ deficit ( $\text{ml} \cdot \text{kg}^{-1}$ )	$23.8 \pm 2.3$	$\text{O}_2$ deficit ( $\text{ml} \cdot \text{kg}^{-1}$ )	$51.9 \pm 9.2$
Anaerobic%	$67.7 \pm 4.9$	Anaerobic%	$80.7 \pm 8.7$

a = one subject did not reach the  $10 \text{ mmol} \cdot \text{l}^{-1}$  level during the test; the value of  $9.7 \text{ mmol} \cdot \text{l}^{-1}$  was used in this single case

TABLE 12. Correlations between the corresponding variables of the MART<sub>4</sub> and Wingate test ( $n = 13$ ). Abbreviations:  $P_{\max}$  = maximal power; Peak BLa = peak blood lactate concentration;  $\text{CMJ}_{\text{rest}}$  = height of counter-movement jump at rest;  $\text{CMJ}_{\text{decr}}$  = percentage decrease of counter-movement jump;  $\text{O}_2$  deficit = oxygen deficit; Anaerobic% = contribution of anaerobic energy yield.

MART <sub>4</sub> vs. Wingate	r
$P_{\max}$ vs. Total work	0.52*
$P_{\max}$ vs. Peak power	0.45
$\text{CMJ}_{\text{rest}}$ vs. Peak power	0.58*
Peak BLa vs. Peak BLa	0.53*
$\text{CMJ}_{\text{decr}}$ vs. Fatigue index	-0.04
$\text{O}_2$ deficit vs. $\text{O}_2$ deficit	0.59*
Anaerobic% vs. Anaerobic%	0.43

\*  $P < 0.05$

## 5.5 Reliability of MART (III, VI)

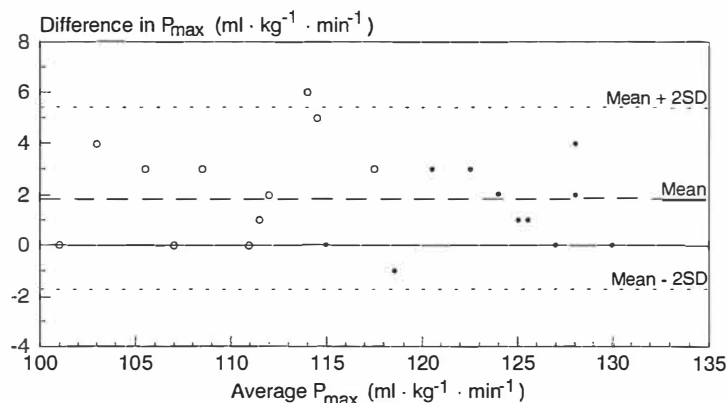


FIGURE 9. Difference against mean for  $P_{\max}$  in sprint runners (dots;  $n = 12$ ) and physically active men (circles;  $n = 13$ ).

TABLE 13. Reliability values of  $MART_4$  in male sprint runners (SR;  $n = 12$ ) and physically active men (PA;  $n = 13$ ). Abbreviations:  $P_{\max}$  = maximal power;  $P_{10mM}$  = power at  $10 \text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $P_{5mM}$  = power at  $5 \text{ mmol} \cdot \text{l}^{-1}$  blood lactate level;  $CMJ_{\text{rest}}$  = height of counter-movement jump at rest;  $CMJ_{\text{decr}}$  = percentage decrease of CMJ during the MART; peak BLa = peak blood lactate concentration; SE = standard error of estimate; CV = coefficient of variation.

SR	$P_{\max}$	$P_{10mM}$	$P_{5mM}$	$CMJ_{\text{rest}}$	$CMJ_{\text{decr}}$	peak BLa
r	0.95***	0.85***	0.87***	0.94***	0.33	0.79**
Slope	0.88	1.03	1.21	0.94	0.53	0.93
Intercept	14.11	-2.70	-16.03	2.91	7.85	-0.30
SE	1.45	3.67	5.41	2.04	6.03	1.42
CV	1.58	3.14	6.41	3.97	34.82	10.77
PA	$P_{\max}$	$P_{10mM}$	$P_{5mM}$	$CMJ_{\text{rest}}$	$CMJ_{\text{decr}}$	peak BLa
r	0.92***	0.80***	0.67***	0.96***	0.56*	0.60**
Slope	0.82	1.01	0.68	1.38	3.42	2.05
Intercept	17.47	-4.23	24.38	0.98	0.96	0.38
SE	1.87	3.94	7.31	1.72	5.66	2.63
CV	2.75	4.86	9.67	3.80	48.68	8.69

\* =  $P < 0.05$ ; \*\* =  $P < 0.01$ ; \*\*\* =  $P < 0.001$

Figure 9 shows that both sprint runners ( $124 \pm 4$  vs.  $125 \pm 5 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) and physically active men ( $108 \pm 5$  vs.  $111 \pm 5 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) ran better in the second  $MART_4$  ( $P < 0.001$ ). Non-significant changes were observed in the  $P_{10mM}$  (sprinters:  $113 \pm 7$  and  $112 \pm 6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ; physically active men:



102 ± 6 and 106 ± 5 ml · kg<sup>-1</sup> · min<sup>-1</sup>), P<sub>5mM</sub> (sprinters: 94 ± 11 and 91 ± 8 ml · kg<sup>-1</sup> · min<sup>-1</sup>; physically active men: 85 ± 9 and 89 ± 9 ml · kg<sup>-1</sup> · min<sup>-1</sup>) or peak BLa (sprinters: 20.0 ± 2.2 and 21.8 ± 1.9 mmol · l<sup>-1</sup>; physically active men: 15.6 ± 3.2 and 14.1 ± 2.0 mmol · l<sup>-1</sup>) between the first and second trial, respectively. The reliability values of the MART<sub>4</sub> for sprint runners and physically active men are shown in Table 13.

## 5.6 Effects of sprint training (V)

As a result of sprint training the maximal power (P<sub>max</sub>) increased by 3.4% (training period: 4.0 ± 2.4 ml · kg<sup>-1</sup> · min<sup>-1</sup>; control period: 1.2 ± 1.6 ml · kg<sup>-1</sup> · min<sup>-1</sup>; P = 0.009) but non-significant changes were observed in the other MART<sub>4</sub> variables (Table 14).

TABLE 14. Results of MART<sub>4</sub> before and after the training (TP) and control (CP) period (n = 9). Values are expressed as mean ± standard deviation. MANOVA indicated the significance of changes and the group by training interactions. Abbreviations: P<sub>max</sub> = maximal power; P<sub>10mM</sub> = power at 10 mmol · l<sup>-1</sup> blood lactate level; P<sub>3mM</sub> = power at 3 mmol · l<sup>-1</sup> blood lactate level; Peak BLa = peak blood lactate concentration; CMJ<sub>rest</sub> = height of counter-movement jump at rest; CMJ<sub>decr</sub> = percentage decrease of CMJ during the MART.

MART	TP/CP	Before	After	MANOVA	
				Changes	Interactions
P <sub>max</sub> (ml · kg <sup>-1</sup> · min <sup>-1</sup> )	TP	118.6 ± 6.0	122.6 ± 4.9	P < 0.001	P = 0.009
	CP	122.9 ± 3.9	124.1 ± 4.7		
P <sub>10mM</sub> (ml · kg <sup>-1</sup> · min <sup>-1</sup> )	TP	112.6 ± 6.8	115.1 ± 7.3	P = 0.184	P = 0.066
	CP	111.9 ± 6.7	111.4 ± 4.4		
P <sub>3mM</sub> (ml · kg <sup>-1</sup> · min <sup>-1</sup> )	TP	80.2 ± 9.2	84.8 ± 10.7	P = 0.156	P = 0.055
	CP	75.7 ± 4.9 <sup>a</sup>	74.8 ± 2.9 <sup>b</sup>		
Peak BLa (mmol · l <sup>-1</sup> )	TP	18.4 ± 2.9	17.6 ± 1.1	P = 0.530	P = 0.071
	CP	20.2 ± 2.1	21.8 ± 1.7		
CMJ <sub>rest</sub> (cm)	TP	44.1 ± 5.9	45.9 ± 5.8	P = 0.223	P = 0.137
	CP	47.2 ± 5.4	47.0 ± 5.4		
CMJ <sub>decr</sub> (%)	TP	16.4 ± 4.1	17.4 ± 4.2	P = 0.726	P = 0.216
	CP	18.2 ± 5.8	16.3 ± 4.4		

a (n = 7); b (n = 6)

The major findings of the correlation analyses were that the volume of extensive interval training correlated positively (r = 0.62; P = 0.040) with the changes of P<sub>3mM</sub> (Figure 10) but correlated negatively (r = -0.68; P = 0.016) with the changes of P<sub>[10mM-3mM]</sub> (Figure 11) during this particular training period. However, it should be mentioned here that the training effects of one subject were decisive for the significant correlation between the extensive intervals and ΔP<sub>3mM</sub> or ΔP<sub>[10mM-3mM]</sub>. The volume of extensive intervals also had a negative

relationship with the peak BLa (Figure 12). Positive relationships were found between the volume of bounding exercises and  $\Delta P_{\max}$  ( $r = 0.64$ ;  $P = 0.032$ ) as well as between the number of bounding and strength exercises and  $\Delta CMJ_{\text{rest}}$  ( $r = 0.60$ ;  $P = 0.044$ ). An unexpected result was that the volume of intensive intervals did not correlate with the changes in  $P_{10mM}$  (Figure 13). Once again, it should be mentioned here that the training effects of one subject were decisive for the non-significant correlation between the intensive intervals and  $\Delta P_{10mM}$ .

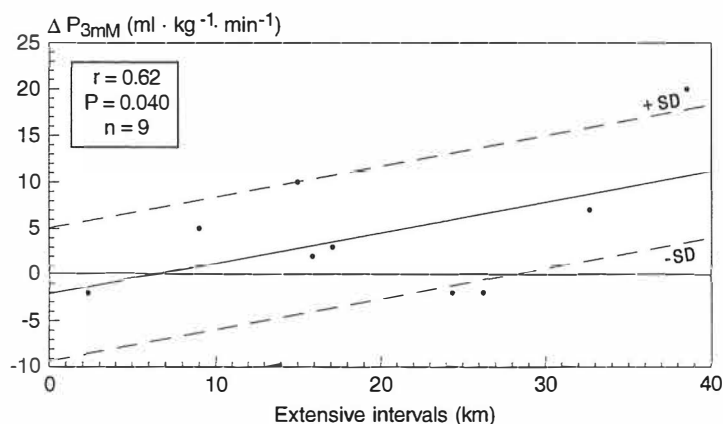


FIGURE 10. Relationship between the volume of extensive intervals and the changes in  $P_{3mM}$  of the MART<sub>4</sub> during a 10-week intensive sprint training period in nine sprint athletes.

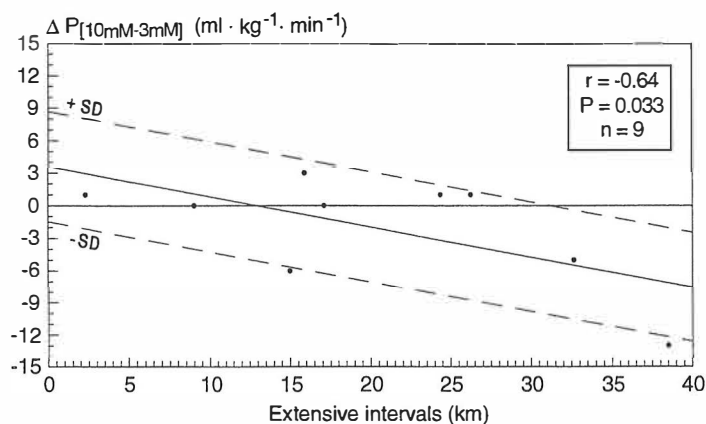


FIGURE 11. Relationship between the volume of extensive intervals and the changes in  $P_{[10mM-3mM]}$  of the MART<sub>4</sub> during a 10-week intensive sprint training period in nine sprint athletes.

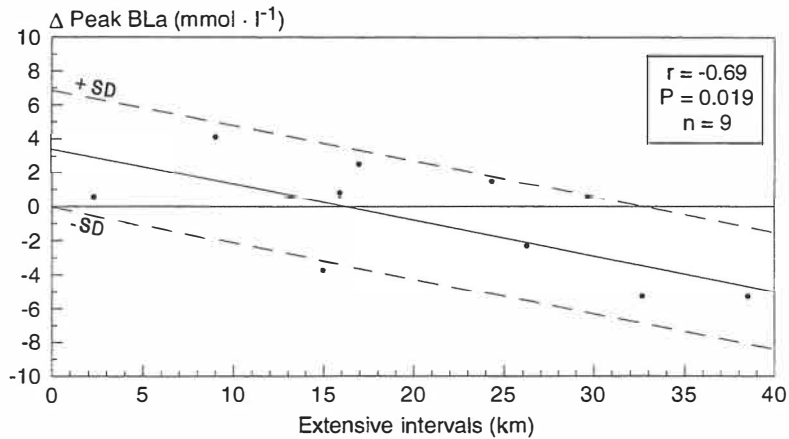


FIGURE 12. Relationship between the volume of extensive intervals and the changes in peak BLa of the MART<sub>4</sub> during a 10-week intensive sprint training period in nine sprint athletes.

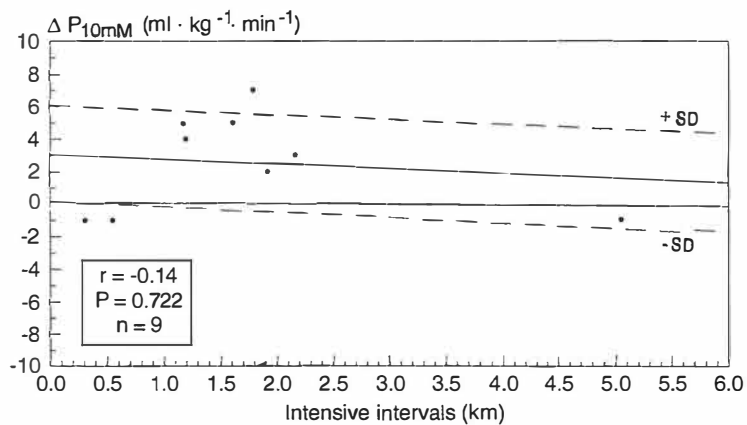


FIGURE 13. Relationship between the volume of intensive intervals and the changes in P<sub>10mM</sub> of the MART<sub>4</sub> during a 10-week intensive sprint training period in nine sprint athletes.

## 6 DISCUSSION

### 6.1 Primary findings

The main findings in the present study were as follows:

1. The MART could be used to determine the different components of anaerobic work capacity. The results of the test included information on (a) the anaerobic work capacity ( $P_{\max}$ ); (b) the anaerobic capacity ( $\Delta P$  or peak BLA); (c) the power at submaximal sprinting ( $P_{10mM}$ ,  $P_{5mM}$  and  $P_{3mM}$ ); (d) the force and velocity characteristics of leg muscles ( $CMJ_{rest}$ ); and the fatigue of the force-generating capacity of the leg muscles ( $CMJ_{decr}$ ). The most important determinants of the maximal anaerobic running performance were maximal running velocity ( $V_{30m}$  or  $V_{20m}$ ), sprinting economy ( $P_{10mM}$ ) and anaerobic capacity ( $\Delta P$  or peak BLA).
2. Maximal power as well as submaximal power indices increased when the grade of uphill running increased from  $1^\circ$  to  $7^\circ$  in the MART.
3. The relative weight of the  $V_{30m}$  and  $CMJ_{rest}$  to determine anaerobic work capacity decreased and the relative weight of peak BLA increased when the grade of uphill running increased from  $1^\circ$  to  $7^\circ$  in the MART.
4. The anaerobic nature of the MART was shown by the  $P_{\max}$ , peak BLA and anaerobic contribution values. The  $P_{\max}$  of the MART<sub>4</sub> ranged from 182% to 262% of  $VO_{2\max}$  in sprint athletes and from 137% to 165% of  $VO_{2\max}$  in endurance athletes. The contribution of anaerobic energy yield ranged from 64% to 68% and the peak BLA attained as high values in the MART as in the 400-m run.

5. Four out of seven correlations between the corresponding variables of the MART<sub>4</sub> and Wingate test were significant but low ( $0.52 < r < 0.59$ ).
6. The reliability figures of the  $P_{\max}$ ,  $P_{10mM}$ ,  $P_{5mM}$  and  $CMJ_{rest}$  were high. However, the retest correlation of the  $CMJ_{decr}$  was low. The reproducibility of the MART<sub>4</sub> variables were better in sprint athletes than in physically active men.
7. The 10-week sprint training period increased the anaerobic work capacity ( $P_{\max}$ ) but not the anaerobic capacity (peak BL<sub>a</sub>), sprinting economy ( $P_{3mM}$  and  $P_{10mM}$ ) nor explosive strength ( $CMJ_{rest}$ ) in well-trained male sprint runners. However, correlation analyses showed that individual changes in the  $P_{3mM}$ , peak BL<sub>a</sub>,  $P_{\max}$  and  $CMJ_{rest}$  were related to the volume of specific training methods.

## 6.2 Determinants of maximal anaerobic running performance

In the present study, the most important determinants of anaerobic work capacity have tried to be described and quantified by the MART<sub>4</sub>, 30-m speed test and aerobic power test. Although peak BL<sub>a</sub> and  $\Delta P$  (the difference between the  $P_{\max}$  and  $VO_{2\max}$ ) are not direct measures, they were used as indices of anaerobic capacity. Power at submaximal blood lactate levels ( $P_{3mM}$  and  $P_{10mM}$ ) were used as an indirect measure of sprinting economy.  $P_{\max}$  is considered to reflect the anaerobic work capacity although it is expressed as oxygen demand like aerobic power.  $P_{\max}$  is the maximal power attained in the MART, not the peak anaerobic power since almost ten repetitive runs with a short recovery and at gradually increasing intensity must have an influence on the  $P_{\max}$ . Moreover, one third of the energy is produced by aerobic pathways during the MART.  $P_{\max}$  includes both the alactic and lactic component while  $V_{30m}$  and  $CMJ_{rest}$  mainly reflect the alactic component of maximal power output since the duration of these tests is less than 8 s.  $CMJ_{decr}$  reflects the fatigue of the force-generating capacity of the leg muscles. Furthermore, the  $VO_{2\max}$  is used as a measure of maximal aerobic power.

As indicated by the correlation and regression analyses, both the  $P_{\max}$  and the 400-m race time (Figures 1, 2 and 3) were a function of maximal sprinting velocity ( $V_{30m}$ ), sprinting economy ( $P_{10mM}$ ) and anaerobic capacity (peak BL<sub>a</sub> or  $\Delta P$ ). The validity of the regression equation for the  $V_{400m}$  was high and could be applied to MART<sub>3</sub> since a high correlation coefficient was observed when the equation was applied to female runners who had performed the MART at the inclination of 3°. Consequently, these variables were the most important determinants of maximal anaerobic running performance and could be used to explain the differences in anaerobic work capacity and to predict 400-m race time. For example, sprinting economy explains the lower  $P_{\max}$  in the power athletes compared to the 400-m runners because the power athletes had lower

$P_{10mM}$  than the 400-m runners while no differences were observed in the other determinants (Table 6). Another example, a possible explanation for the difference in the  $P_{max}$  between the long and middle distance runners, could be that the long distance runners had lower anaerobic capacity (peak BLA and  $\Delta P$ ) than the middle distance runners.

Non-significant differences in the  $P_{max}$ ,  $P_{10mM}$  and peak BLA between middle distance and 400-m runners suggest that these two groups had similar anaerobic abilities. The only significant differences between these two groups were observed in the  $V_{30m}$ ,  $\Delta P$  and  $CMJ_{rest}$ . These findings were supported by the results during the competitive season since some middle distance runners ran a faster 400 m than some of the 400-m runners confirming that these groups overlap in terms of 400-m performance and anaerobic abilities. Houmard et al. (1991) have also suggested that middle distance running performance is strongly influenced by not only aerobic power but also by anaerobic ability.

In the present study, peak BLA in the  $MART_4$  and  $\Delta P$  have been used as indices of anaerobic capacity, although the validity of the  $\Delta P$  and peak BLA to quantify anaerobic capacity is questionable (Green & Dawson 1993, Gastin 1994). However, correlation and variance analyses revealed that sprint and middle distance runners who should have high anaerobic capacity had the highest peak BLA and  $\Delta P$  values (Table 6) suggesting that peak BLA and  $\Delta P$  reflect anaerobic capacity.  $\Delta P$  values in the present study (Table 6) were of the same magnitude as  $O_2$  deficit values in the constant speed exhaustive exercise lasting 60 s (Hermansen & Medbø 1984) suggesting that there might be a relationship between  $\Delta P$  and  $O_2$  deficit and the  $\Delta P$  could be used as an estimate of anaerobic capacity. The fact that the  $P_{max}$  and  $VO_{2max}$  are power indices and were measured from two separate tests suggests, however, that  $\Delta P$  is an indirect index, which can not be used as a direct measure of the anaerobic capacity.

A new sphere of interest in the present study was the economy of anaerobic sprint running. The term sprinting economy is introduced because the term running economy has been widely used to describe  $VO_2$  at different distance running speeds. Mero et al. (1992) have suggested that in sprint running the economy could be evaluated by calculating the actual mechanical efficiency, measuring integrated EMG vs. resultant force ratio and determining blood lactate vs. running velocity ratio at submaximal blood lactate levels. The determination of mechanical efficiency is very difficult in sprint running because of calculations of the exact work and input of energy. The results of different studies are also contradictory (Cavagna & Kaneko 1977, Kaneko et al. 1981, Kaneko et al. 1985). Little is known about the use of EMG to determine sprinting economy and it is not a practical method to evaluate economy in sprint athletes. The determination of sprinting economy from blood lactate measurements is based on the idea that the faster the speed at certain blood lactate levels the better the economy and technique are of a particular sprinter.

In the MART, submaximal power indices ( $P_{3mM}$ ,  $P_{5mM}$  and  $P_{10mM}$ ) are suggested as indicators of the sprinting economy. High correlations between the velocity in the 400-m race and the  $P_{10mM}$  in the  $MART_4$  and  $MART_5$

(Figures 1 and 2) suggest that  $P_{10mM}$  could be used as an index of sprinting economy for 400-m runners. Our present findings that 400-m and middle distance runners had the highest  $P_{10mM}$  values (Table 6) support the hypothesis that the  $P_{10mM}$  is an important determinant for distances from 400 m to 1500 m where anaerobic glycolysis covers a great proportion of the total energy yield. This is in agreement with a recent study which demonstrated that blood lactate concentration has a mean value of  $10 \text{ mmol} \cdot \text{l}^{-1}$  during the 400-m sprint (Nummela et al. 1992). Schnabel & Kindermann (1983) have also observed that a small increase in blood lactate concentration during a non-exhaustive 40-s run is associated with excellent performance in running events.

The purpose of the CMJ performed before and after the MART was to evaluate muscle strength and power normalised to body weight as well as fatigue in the MART. As expected (Bosco et al. 1987) the power athletes and 400-m runners had the highest  $\text{CMJ}_{\text{rest}}$  in the present study (Table 6). The  $\text{CMJ}_{\text{rest}}$  did not correlate with the 400-m race time (Figures 1 and 2) suggesting that neuromuscular power estimated by the CMJ is not an important factor determining performance in the 400-m run. One reason for this may be that knee and ankle extensors are mainly responsible for force production in CMJ (Bobbert et al. 1986) but in running knee and hip flexors also play an important role (Mero et al. 1992). Higher correlation coefficients were observed for the  $V_{30m}$  than for the  $\text{CMJ}_{\text{rest}}$  in correlation analysis with 400-m race time and with the  $P_{\text{max}}$  suggesting that the  $V_{30m}$  is a better variable than the  $\text{CMJ}_{\text{rest}}$  to describe force and velocity characteristics of the neuromuscular systems in sprint and endurance runners.

The purpose of  $\text{CMJ}_{\text{decr}}$  was to evaluate fatigue in the MART. The results showed that the long distance runners tolerated fatigue better than the 400-m runners, power athletes and control group. This could be explained by the training background and fibre type composition since long distance runners are supposed to have lower FT / ST ratio (e.g. Gollnick et al. 1972, Gregor et al. 1979) and fast twitch fibres are more susceptible to fatigue than slow twitch fibres (Tesch et al. 1985). The highest CMJ value was attained at rest in the  $\text{MART}_4$  and after the fourth run in the  $\text{MART}_5$ , when the blood lactate concentration was less than  $5 \text{ mmol} \cdot \text{l}^{-1}$ . The height of the CMJ started to decrease after the eighth run when the blood lactate concentration was over  $8 \text{ mmol} \cdot \text{l}^{-1}$  (Figure 5). A similar decrease in the force-generating capacity of sprint trained athletes has also been observed at the same blood lactate concentration during 400-m run (Nummela et al. 1992).

### 6.3 Effects of treadmill inclination

The maximal power ( $P_{\text{max}}$ ) increased with the treadmill inclination in the MART (Table 6). This is in line with the study of Olesen (1992), who observed that the accumulated oxygen deficit increased with the treadmill inclination until a grade of 15% ( $8.5^\circ$ ). The increased  $P_{\text{max}}$  could reflect inclination-induced changes in the muscle mass involved in running since active muscle mass is

related to maximal anaerobic energy production (Saltin 1990) and anaerobic energy yield was increased with inclination in the present study. However, energy output and carbohydrate utilisation are similar during level and uphill running, at least at submaximal running velocities (Costill et al. 1974) suggesting that active muscle mass is equal during running at different inclinations. Furthermore, it is improbable that the increased mass of the working muscles from 1° to 7° of uphill running can explain a difference of 27% in  $P_{\max}$  since during level running ~15 kg of muscles are already active (Savard et al. 1987).

It is also possible that the calculated oxygen demand from the  $VO_2$  of submaximal running intensities underestimates the true energy expenditure during supramaximal work (Daniels 1985, Saltin 1990). Mechanical efficiency may be lower in supramaximal than in submaximal running and the difference may be greater during running on low slopes (Kaneko et al. 1985, Olesen 1992) although some other reports (Cavagna & Kaneko 1977, Kaneko et al. 1981) have shown that the efficiency of positive work improves with higher running velocities. However, the difference in the  $P_{\max}$  between the different inclinations remained whether the oxygen demand was calculated from the individual  $VO_2$  of submaximal intensities or from the ACSM formula for inclined treadmill running (ACSM 1986).

Another plausible explanation for the observed increase in the  $P_{\max}$  with the treadmill inclination is that the untrained subjects were not used to run at high speeds and therefore they were not able to produce high power output at low inclinations when the running speed increased to a high level. At the grade of 1° the velocity increases to the level where the velocity characteristics of the neuromuscular system were limiting the subjects' anaerobic work capacity. The highest correlation coefficients between the  $P_{\max}$  and  $CMJ_{\text{rest}}$  and between the  $P_{\max}$  and  $V_{20m}$  in the MART<sub>1</sub> further suggest that the relative importance of force and velocity characteristics of the neuromuscular system is high when the treadmill inclination is low (Table 8).

The average  $O_2$  deficit and the peak BLa were lowest in the MART<sub>1</sub> suggesting that lactic capacity was not completely used and the importance of metabolic factors to determine the  $P_{\max}$  is low at the grade of 1°. The increased weight of the peak BLa coefficient in a regression equation with the increased inclination further supports that the measured lactic capacity is related to the grade of uphill running (Table 10). In addition, the highest correlation coefficient between the  $P_{\max}$  and  $P_{10mM}$  in the MART<sub>1</sub> suggests not only that the importance of the  $P_{10mM}$  reduces with the increased grade of the uphill but also that the importance of lactic capacity increases with the increased inclination. These are in line with the findings that  $O_2$  deficit increased with the inclination (Olesen 1992). However, the correlation coefficient between the  $P_{\max}$  and peak BLa was lower in the MART<sub>7</sub> than in the MART<sub>1</sub> or MART<sub>4</sub>. One possible explanation for this might be that the validity of blood lactate to quantify muscle lactate production and lactic energy yield is questionable since before an equilibrium is reached between muscle and blood a large fraction of the lactate has been metabolised (Hermansen & Stensvold 1972).



The  $P_{10mM}$  and  $P_{5mM}$  also increased with the treadmill inclination although no significant differences were observed between the MART<sub>4</sub> and MART<sub>7</sub> (Table 7). Blood lactate is a rough indication of glycolysis and also reflects the use of fast twitch muscle fibres which are specialised to glycolytic energy production (Tesch et al. 1981, Jacobs 1986). Contraction velocity has been found to influence muscle fibre recruitment pattern (Lesmes et al. 1979) suggesting that the highest blood lactate values at submaximal velocities in the MART<sub>1</sub> resulted from the highest velocity and possibly from the greatest involvement of fast twitch muscle fibres. Furthermore, the rate of heat production in human skeletal muscle is six times greater in fast twitch than in slow twitch muscle fibres in an isometric contraction (Bolstad & Ersland 1978) suggesting that the energy consumption per unit of tension produced is higher and the efficiency is lower for fast twitch fibres as compared to slow twitch ones. Taken together, this further supports the previous discussion that  $O_2$  demand calculation from the  $VO_2$  of submaximal runs underestimates the power at low inclinations and high velocities. Furthermore, similar  $VO_2$  curves during each MART suggest that the power gap between the different MARTs is not as great as the  $O_2$  demand calculation indicates since the rate of  $VO_2$  on-response depends on the intensity of the exercise (Margaria et al. 1965).

High correlation coefficients between the  $P_{max}$ ,  $P_{10mM}$  and  $P_{5mM}$  of the MART<sub>1</sub> and MART<sub>4</sub> suggest that these two test protocols measure the anaerobic running performance characteristics similarly (Table 9). These correlation coefficients were equal to the test-retest correlations measured at the grade of 4° (Table 13). On the other hand, the correlation coefficients between the MART<sub>7</sub> and the other MART protocols were low.

## 6.4 Validity of MART

The validity of the MART was verified by evaluating the anaerobic energy production during the test; by comparing the results of the MART<sub>4</sub> between the different groups of athletes, which were known to differ in their anaerobic performance characteristics; and by comparing the results of the MART<sub>4</sub> with the results of the Wingate test, which has been most frequently used by many authors since its first description (Ayalon et al. 1974) and is held to be valid (Bar-Or 1987). The duration of the runs is critical when measuring the anaerobic capacity. To ensure the high degree of specificity, the runs should be long enough to exhaust the anaerobic processes and short enough to keep the proportion of the aerobic energy yield as small as possible (Vandewalle et al. 1987). The 20-s running time was selected because: (1) the phosphagen stores are mainly used up and they have been shown to not be depleted until maximal power is approached (Saltin & Essén 1971, Hirvonen et al. 1987); (2) the contribution from glycolytic energy sources has been found to be high and to increase the higher the intensity of exercise (Hermansen 1971, Di Prampero 1981); and (3) the contribution from aerobic energy production has been seen to be small (Di Prampero 1981).

It is impossible to quantify the total accumulated O<sub>2</sub> deficit or the contribution of anaerobic energy yield in the MART, because during the recovery periods myoglobin oxygen stores and phosphocreatine stores were partly replenished and lactate was partly removed from the working muscles to blood and other tissues like liver and heart (Stainsby & Brooks 1990). As a result of gradually increased O<sub>2</sub> demand and incomplete recovery of phosphocreatine stores the anaerobic capacity was exhausted by increasing the rate from the first run to the end of the MART. That is why the average O<sub>2</sub> deficit of all completed 20-s runs was used as an estimate of the anaerobic energy yield in the MART. The average contribution of anaerobic energy yield ranged from 64% to 68% in the MART at different treadmill inclinations. The anaerobic contributions correspond to the values reported earlier for the maximal exercises of 60 s (Thomson & Garvie 1981, Medbø & Sejersted 1985, Nummela & Rusko 1995) suggesting that the MART is highly anaerobic by nature. The anaerobic contribution for the Wingate test has been determined to be between 71% and 87% (Bar-Or 1987, Kavanagh & Jacobs 1987, present study). It should be recognised here that the duration of the Wingate test was 30 s and 20-s runs were used in the MART. The difference in the anaerobic contribution between the Wingate test and the MART would have been smaller if only the last 20 s was used for calculation in the Wingate test.

The anaerobic nature of the MART is also shown by the P<sub>max</sub> values since the P<sub>max</sub> was from 182% to 262% of VO<sub>2max</sub> in sprint athletes and from 137% to 165% of VO<sub>2max</sub> in endurance athletes. Furthermore, the athletes in the present study, who were expected (Kindermann & Keul 1977, Thomson & Garvie 1981, Boileau et al. 1982) to have high anaerobic work capacity, had higher P<sub>max</sub> than the other athletes and control group (Table 6). According to the ACSM formula the mean power of 119 ml · kg<sup>-1</sup> · min<sup>-1</sup> has to be generated for running 400 m in 45 s (ACSM 1986). In the above calculation it was supposed that air resistance corresponds to the inclination of 1° on a treadmill. The results of the present study showed that untrained and sprint trained subjects were able to attain the oxygen demand of 108 ± 6 and 125 ± 4 ml · kg<sup>-1</sup> · min<sup>-1</sup>, respectively, in the MART<sub>4</sub>. The above example demonstrates that the P<sub>max</sub> is at the same level as the oxygen demand during the 400-m run, and 400 m is known to be a highly anaerobic distance of running. In addition, a recent finding that a significant positive relationship exists between the P<sub>max</sub> of the MART and maximal accumulated oxygen deficit (Maxwell & Nimmo 1996) is well in line with the results of the present study.

Peak blood lactate concentrations of about 20 mmol · l<sup>-1</sup> after races of 400 m and 800 m have been mentioned, whereas in individual cases, values as high as 25 mmol · l<sup>-1</sup> are possible (Kindermann & Keul 1977). In untrained subjects the exercise comes to an end when the blood lactate has reached the concentration of 15 - 20 mmol · l<sup>-1</sup> (Thomson & Garvie 1981). In the present study, the peak blood lactate concentrations of 17 ± 3, 10 ± 2 and 14 ± 3 mmol · l<sup>-1</sup> were obtained for male sprint and endurance runners and physically active men, respectively. These values suggest that it is possible to attain a high level of lactic acidosis in the MART<sub>4</sub>. Furthermore, the significant correlation between the P<sub>max</sub> of the MART<sub>5</sub> and MART<sub>4</sub> and the average velocity in the

400 m run demonstrated that the maximal performance in the MART and in the 400 m run were closely related to each other. The constant velocity during the runs in the MART suggests that anaerobic capacity could not be totally depleted at the end of the test since the velocity decreasing phase of the run can not be utilised as is possible during the 400-m run. This is the problem with all constant load tests. Psychological factors also affect  $P_{\max}$  like in all maximal anaerobic tests but the influence of mental factors like motivation is difficult to quantify.

In the MART, submaximal power indices ( $P_{3mM}$ ,  $P_{5mM}$  and  $P_{10mM}$ ) are suggested as indicators of the sprinting economy. However, sprinting economy is a slightly misleading term since 1/3 of the total energy yield is produced by aerobic pathways in the MART and blood lactate can not be considered to simply represent the product of lactate formation in skeletal muscles. Previous studies have shown that net lactate output from muscle contracting *in situ* is related to the intensity of stimulation (Brooks 1991). However, lactate removal from blood to the contracting muscles and to other tissues as well as beta-adrenergic agonists (e.g. epinephrine) have a major effect on the magnitude of the blood lactate concentration (Brooks 1991). Furthermore, the rate of lactate removal from the blood by active muscles is related to the concentration of lactate in the blood (Stainsby & Brooks 1990).

Previous studies have shown that the effect of high aerobic power is limited in exercises of anaerobic nature like the MART (Schnabel & Kindermann 1983, Nummela & Rusko 1995). The rate of  $VO_2$  increase at the onset of supramaximal exercise is of greater importance to aerobic energy expenditure than maximal oxygen uptake although the time course of  $VO_2$  depends on the  $VO_{2\max}$  (Hickson et al. 1978). Differences in oxygen uptake during the MART should primarily affect submaximal power indices. However, no relationship could be observed between  $VO_2$  and  $P_{3mM}$ ,  $P_{5mM}$  or  $P_{10mM}$ . One should notice here that the measurement of pulmonary oxygen uptake during supramaximal short-term exercise might not be valid since it need not precisely reflect oxygen consumption at the mitochondrial level.

Previous studies have also demonstrated that phosphocreatine is the main energy source at the onset of exercise and PCr stores decreased exponentially during short-term intensive exercises (Chasiotis et al. 1987, Hirvonen et al. 1992). This suggests that the utilisation of high-energy phosphate stores may also affect submaximal power indices of the MART. Although Rehunen et al. (1982) have shown that PCr stores at rest are nearly the same in endurance and sprint athletes, differences exist between the different muscle fibres. Furthermore, in short-term supramaximal exercise the rate of PCr depletion may differ between the muscle fibre types (Rehunen et al. 1982), and sprint running performance depends on the ability to use high-energy phosphates at the beginning of exercise (Hirvonen et al. 1987). Moreover, the utilisation of high energy phosphates affect energy production during the whole MART since PCr stores are partly replenished during recovery periods.

Submaximal power indices can not be used to quantify sprinting economy, since blood lactate is a function of lactate production, removal and clearance, and changes in any of these parameters will affect blood lactate

concentration. Instead, they can be used as a practical index to reflect sprinting economy in sprint athletes since a significant correlation was observed between the  $P_{10mM}$  and the average velocity in 400-m run. In addition, the speeds corresponding to the 3 and 10  $\text{mmol} \cdot \text{l}^{-1}$  blood lactate level did not correlate with any other properties significant for the performance in the 400-m. Schnabel & Kindermann (1983) have also observed that a small increase in blood lactate concentration after short-term non-exhaustive sprinting is associated with excellent performance in running events. The submaximal power indices are also sensitive to sprint training since a positive correlation was observed between the volume of extensive interval training and  $\Delta P_{3mM}$  and the velocities at the  $P_{3mM}$  correspond to the velocities in the extensive intervals.

In order to validate the  $MART_4$ , its results were also compared with the corresponding variables of the Wingate test (Table 12). It should be mentioned here that in comparison of  $O_2$  deficit and anaerobic contribution between the two tests it has been assumed that ACSM formula for the inclined treadmill and leg ergometer were comparable. Four variables in the  $MART_4$  ( $P_{max}$ , peak BL<sub>a</sub>,  $CMJ_{rest}$  and  $O_2$  deficit) correlated significantly with the corresponding variables of the Wingate test suggesting that the  $MART_4$  measures at least partly the same anaerobic properties as the Wingate test. Low correlations between the corresponding variables in the  $MART_4$  and Wingate test could be explained by the differences between the two tests. First, the MART is a running test and the Wingate test a cycling test and different muscle groups are involved in running compared with cycling. Second, running is a stretch-shortening cycle exercise but in cycling concentric work is dominant. Third, the MART consisted of  $n \times 20$ -s running bouts and total duration of the test may be over 15 min while the Wingate test is a standard 30-s test. The comparison of the tests is difficult because the way of doing them is different: submaximal work loads are included in the MART and it is an interval test while the Wingate test is a short-term all-out test.

## 6.5 Reliability of MART

The correlations between the first and second  $MART_4$  were high and the coefficients of variations were low (Table 13). The  $P_{max}$  was higher in the second test than in the first one (Figure 9) probably suggesting a learning process since the difference between the first and second trial was slightly higher in physically active men than in sprint runners who were familiar with anaerobic training and testing. In addition, the second MART could not be performed without knowing the result of the first test. Similar change between two trials has also been found in a cycle ergometer test, where the author indicates that the increase was due to the fact that the subjects were not familiar with the test (Simoneau et al. 1983). According to Vandewalle et al. (1987) the retest correlations of the MART are high since for constant load tests they normally range around 0.77.

The reliability of the peak BLa measurements was low but significant. Vandewalle et al. (1987) revealed indices from 0.87 to 0.91. The coefficient of variation of peak blood lactate was high suggesting that the reproducibility of peak blood lactate measurements was not very good. Another possible explanation for the differences in the peak BLa between the first and the second test could be motivation, but this is a very difficult variable to control. However, the higher retest correlation of the peak BLa for the sprint runners compared to the physically active men suggests that motivation and a familiar test situation may influence the peak BLa values in the MART.

The reliability figures calculated for the  $CMJ_{rest}$  agree with values found in the literature, ranging from 0.92 to 0.98 (Vandewalle et al. 1987). The reason for this is probably the simplicity of the test. The reliability of the  $CMJ_{decr}$  was low and it was significant only with physically active men (Table 13). The test-retest reliability of the fatigue index in the Wingate test has also been reported to be low ( $0.43 < r < 0.74$ ; Vandewalle et al. 1987) suggesting that fatigue indices can give only a rough estimate of the fatiguability of subjects. The reason for this might be that not only numerous physiological but also motivational, methodological and tactical factors affect the fatigue indices calculated as the relative decrease of force or power.

## 6.6 Effects of sprint training

The improvement of 3.4% in the maximal power in the present study represented a greater difference than the measured test-retest variability for the same sprinters suggesting that the anaerobic work capacity had improved during the sprint training period. In untrained subjects, short-term (8 weeks) sprint or interval training has previously been shown to result in improvements of 6 - 28% in sprint performance (Sharp et al. 1986, Nevill et al. 1989). The difference in the results between untrained subjects and trained sprinters could be explained by their training background since untrained subjects are able to obtain greater improvements in muscular performance than trained athletes. Häkkinen (1989) has observed that untrained subjects can obtain an initial increase of 10% or even more in muscular strength only after two weeks of intensive training but in strength athletes the increase in muscular strength is less than 10% during 12-week period of intensive strength training. The comparison of the results of the  $MART_4$  at the end of the training and control periods revealed that the sprinters had increased their  $P_{max}$  less during one year (1.2%) than during the 10-week experimental training period (3.4%) suggesting that seasonal changes are greater than the annual development of the athletes. Long term change in anaerobic running performance in the present study was somewhat lower than Cadefau et al. (1990) have measured in young sprint athletes. They observed that the performance of 16-year old athletes was increased from 3% to 5% in 60 m and 300 m during an 8-month sprint training period.

It was expected that the extensive interval training would increase the  $P_{3mM}$  since the relative intensity of the extensive interval training and the  $P_{3mM}$  are at the same level (55% - 80% of the best performance). In addition, running velocities at the  $P_{3mM}$  were 4.9 and 5.2  $m \cdot s^{-1}$  before and after the training, respectively, corresponding to the velocities used in the extensive interval training (Table 5). The positive correlation between the volume of the extensive interval training and  $\Delta P_{3mM}$  was in line with to our hypothesis and suggested that the volume of the extensive intervals has an important role in the improvement of sprinting economy at submaximal sprinting (< 80% of the best performance). The effect of the extensive interval training was quite specific since the correlation between the  $\Delta P_{[10mM-3mM]}$  and the volume of the extensive intervals was negative. The differences in the effects between extensive and intensive interval training are supported by Fox et al. (1977) since they observed that the major difference between the low and high power output interval training program was that the low power group exhibited a significantly greater decrease in blood lactate at the same submaximal work rate.

The mechanisms responsible for the increase in the  $P_{3mM}$  due to the extensive intervals are not apparent and simple. However, there are several possibilities. Endurance training has been shown to enhance the efficiency of lactate removal in rats (Donovan & Pagliassotti 1990) suggesting that extensive intervals, in which a great proportion of energy is delivered by aerobic pathways, may influence the  $P_{3mM}$  by enhancing the efficiency of lactate removal. This explanation is supported by the positive correlation between the  $P_{3mM}$  and the anaerobic threshold (i.e. the highest level of energy expenditure at which the maximal elimination rate of lactate can be achieved) (Aunola 1991). It is also possible that endurance training influences the transformation of muscle fibre type since Simoneau et al. (1986) have observed a percentage increase of the slow twitch muscle fibres after an interval training programme. This explanation is also supported by a positive correlation between the  $P_{3mM}$  and the anaerobic threshold since the anaerobic threshold probably depends on muscle fibre type composition (Aunola et al. 1988).

Other possible mechanisms for the increase in  $P_{3mM}$  by extensive intervals might involve a greater oxidation of pyruvate and a smaller lactic acid production and / or a greater utilisation of high energy phosphates. A negative correlation between the volume of extensive intervals and  $\Delta peak BLa$  supports the first mechanisms although it could also be explained by enhanced efficiency of lactate removal. These results are supported by Fox et al. (1977) since they have observed that a low power output interval training program decreased the lactic acid production during a 2-min exhaustive run. The  $P_{3mM}$  is most likely also associated with high energy phosphate utilisation since during the first part of the MART the energy yield is probably mainly covered by the phosphagen stores (Saltin & Essén 1971, Cheetham et al. 1986). Therefore, the increased  $P_{3mM}$  might result from increased high energy phosphate utilisation. Schnabel & Kindermann (1983) have also suggested that a small increase in blood lactate concentration during non-exhaustive sprinting is associated with high energy phosphate utilisation.

It was also expected that the intensive interval training would increase the  $P_{10\text{mM}}$  or  $P_{\text{max}}$ . The relative intensity of the  $P_{10\text{mM}}$  ranged from 85% to 95% of the  $P_{\text{max}}$  and the running velocities at the  $P_{10\text{mM}}$  and at the  $P_{\text{max}}$  ranged from 6.1 to 7.6  $\text{m} \cdot \text{s}^{-1}$  and from 6.7 to 8.0  $\text{m} \cdot \text{s}^{-1}$ , respectively. Thus, the relative and absolute velocities used during intensive interval training corresponded to the velocities of the  $P_{10\text{mM}}$  and  $P_{\text{max}}$  (Table 5). However, the volume of intensive intervals was not related to the changes in the  $P_{10\text{mM}}$  and  $P_{\text{max}}$  suggesting that velocities at maximal or near maximal blood lactate concentrations are not influenced by one single training method. A positive correlation between the volume of bounding exercises and  $\Delta P_{\text{max}}$  suggests that training which utilises various jumping exercises with high contraction velocities and with great reaction forces results in great increases in exercises including stretch-shortening cycles such as sprint running.

The present results showed that 400-m runners had higher  $P_{10\text{mM}}$  than untrained subjects, power athletes and distance runners (Table 6). This suggests that an anaerobic type of training decreases the blood lactate accumulation and increases the sprinting economy at high sprinting velocities. Consequently, the frequency, intensity and quality of sprint training might be more decisive than the volume of training in improvements of running velocities at higher blood lactate concentrations. In addition, as pointed out by Häkkinen (1989) one important point concerning adaptive responses in highly trained athletes is that the training should be individually programmed and changed periodically in order to obtain the desired results.

Unexpected results in the present study were that the height of the CMJ and peak BLa did not increase during sprint training suggesting that peak power and anaerobic capacity had not changed during the sprint training period. This is contradictory to previous results since many studies have shown that intensive sprint training increased the peak power and / or peak blood or muscle lactate concentration in the anaerobic exercise test (Ready et al. 1981, Sharp et al. 1986, Jacobs et al. 1987, Nevill et al. 1989). However, Medbø & Burgers (1990) did not observe any changes in the peak BLa during a 6-week training period but they found a significant increase in the accumulated oxygen deficit indicating that anaerobic capacity was improved by sprint training.

There are some possible explanations for the unchanged anaerobic capacity. One is that the present subjects were trained sprinters whose initial anaerobic capacity was already at a high level. We can not expect that the sprinters, who had peaked their anaerobic capacity during the indoor season before the study, could attain as great improvements as initially untrained subjects in the previous studies (Ready et al. 1981, Sharp et al. 1986, Jacobs et al. 1987, Nevill et al. 1989). Another possible explanation could be that the training volume of the sprinters during the 10-week training period was so high (6.3 exercise / week) that the anaerobic capacity could not be improved until the sprinters reduced their training volume during the following competitive season. Several investigations support the idea that the reduced training of the trained athletes enhanced the performance (Costill et al. 1985, Shepley et al. 1992).

The low reproducibility of the peak BLa might also influence the unchanged results of the present study since the variation of the peak BLa measure might exceed the actual change of the value (Table 12). However, the accuracy of the measurement can not be the explanation for the unchanged  $CMJ_{rest}$  since the reproducibility of the CMJ was high. Probably, the low volume of bounding and strength training might be one reason for the unchanged  $CMJ_{rest}$  since the volume of bounding and strength training was related to the  $\Delta CMJ_{rest}$  in the present study. In addition, Häkkinen (1989) has pointed out that the intensity of the strength training seems to be more important than the volume to induce positive responses in muscle strength. A negative correlation between the volume of extensive intervals and  $\Delta peak$  BLa suggests that the other exercise types might have an opposite or delayed effect on the anaerobic capacity.

## 6.7 Limitations and future of MART

The results of the present study showed that the validity and reliability of the MART is comparable to other anaerobic test methods but unlike the other anaerobic tests the MART provides information on the different determinants of anaerobic work capacity. In addition, submaximal power indices could be used to determine training zones for interval training of sprinters like so-called aerobic-anaerobic threshold tests are used in endurance sports (e.g. Kindermann et al. 1979). However, there are several limitations which should be considered when using the MART. Power in the MART is expressed as the oxygen demand of running since the mechanical power (W) is difficult to measure in treadmill running. The problem is that the determination of oxygen demand is based on the assumptions that a linear relationship exist between the energy consumption and running velocity at submaximal and maximal running; the efficiency of running does not change in fatigue; and individual differences in running efficiency are negligible. Medbø et al. (1988) have suggested that the relationship between exercise intensity and steady-state  $O_2$  uptake at submaximal intensities should be determined individually since 16% variation was observed in running economy between subjects. In study II, the  $O_2$  demand of 20-s runs was determined by extrapolating the  $O_2$  uptake at submaximal velocity to higher velocities. The source of error in this procedure is that there is a time delay between  $O_2$  uptake at muscular and mouth level. Furthermore, the retest correlation of  $O_2$  deficit and anaerobic contribution were low in the MART (III). The inaccuracy of  $O_2$  demand determination can be avoided by using velocities instead of power units.

The values of maximal anaerobic power obtained with different anaerobic test protocols are different but generally well correlated. The maximal power measured by the MART may not correspond with the true maximal anaerobic power since 35% of the energy is produced by aerobic pathways; maximal power output is measured at the time when muscle acidosis already affects the force-generating capacity of working muscles; and maximal power depends on



the slope of the treadmill. However, these factors are problems in most of the existing anaerobic test protocols (Vandewalle et al. 1987). The  $P_{\max}$  in the MART is a measure of anaerobic work capacity which mainly depends on the lactic power and capacity and to a minor extent on alactic anaerobic power. Shorter working periods, longer resting periods and smaller number of runs would increase the role of alactic power but, on the other hand, the increased velocity would probably increase the risk of injury. Therefore, counter-movement jumps and maximal 20-m or 30-m speed test on a track are recommended to get an estimation of the neuromuscular and alactic power of an athlete.

At present, a universally accepted method to quantify anaerobic capacity does not exist (Green & Dawson 1993). The oxygen deficit has the potential to quantify anaerobic capacity but its validity to estimate the true energy cost is less certain. The source of error in  $O_2$  deficit measurement is the determination of the oxygen demand. Since  $O_2$  demand can not be directly measured it is estimated from the  $VO_2$  of submaximal exercise intensities. Another assumption in  $O_2$  deficit measurement is that mechanical efficiency is not affected by the increased temperature and fatigue during the exhaustive exercise. Such estimations are likely to underestimate the true energy expenditure during maximal work since mechanical efficiency may be lower in exhaustive than in submaximal exercise (Kaneko et al. 1985).

The validity of the peak BLA as an indicator of muscle lactate concentration and anaerobic capacity is limited, because there is not a simple causal relationship between the glycolytic energy production and blood lactate concentration. However, significant negative correlations between peak BLA and running times over 400 m (Fujitsuka et al. 1982, Nummela et al. 1992) suggest that peak blood lactate concentration can be used as a rough estimate of anaerobic capacity. Therefore, the measurement of peak BLA could be a better way than oxygen deficit to estimate anaerobic capacity in the MART. In the present study,  $\Delta P$  was also used as an indicator of anaerobic capacity and based on the regression analysis it seemed to be as good indicator of anaerobic capacity as peak BLA (Figures 1 and 2). A practical problem with  $\Delta P$  is that two different tests are needed to determine  $\Delta P$  (i.e. MART and the maximal aerobic power test).

In the first two studies of the MART (I, Paavolainen et al. 1994), the CMJs were performed after each run to evaluate the development of muscle fatigue during the MART. Since the CMJs are performed 15 - 35 s after exhaustion and due to fast recovery during the first seconds after exhaustion, they may not fully reveal the fatigue of the neuromuscular system in the MART. Furthermore, the test-retest correlation coefficient of  $CMJ_{\text{decr}}$  was small suggesting that the variability of the  $CMJ_{\text{decr}}$  must be reduced or another method should be developed to measure the force-velocity characteristics and fatigue of the neuromuscular system during the MART. Efforts to minimise the variability must recognise that the variance of  $CMJ_{\text{decr}}$  is always higher than that of the CMJ both in the non-fatigued and fatigued condition since it will be derived from CMJ measures with corresponding errors. Although the CMJ curve could be used to estimate the force-generating capacity of the leg muscles

relative to the blood lactate concentration and running velocity, it is recommended that the CMJs should be performed only at rest and after exhaustion since a great number of jumps may affect the development of fatigue and maximal power especially in sprint runners (Paavolainen et al. 1994).

The major focus of the present study was to develop an anaerobic test method, which could be used to determine the most important determinants of maximal anaerobic performance, and which could be useful for sprint coaches and athletes in practice. Minor emphasis was placed on the metabolic and physiological bases of anaerobic capacity or on the development of muscle fatigue during the MART. Therefore, further research is needed to examine both the neuromuscular and metabolic mechanisms of neuromuscular fatigue during the MART. Recent evidence suggests that  $n \times 20$ -s running bouts with 100-s recovery and 4° inclination is the best protocol in which both the force-velocity and metabolic components of the maximal anaerobic performance could be equally utilised but further research may reveal that various combinations of running and recovery times or inclinations are needed to maximise the determinants of anaerobic performance capacity in different groups of athlete. Consequently, the effects of running and recovery time on the anaerobic work capacity in the MART should be investigated.

Although the applicability of the MART to sprint running was indicated in the present study, further research is needed to develop the MART for different sports and different ergometers. First attempts have already been made to apply the principles of the MART to the bicycle ergometer and the results were quite promising (Tossavainen et al. 1996). The bicycle modification of the MART could be used in rehabilitation studies and in older people as well as in sports like cycling or skating, in which muscles used in cycling play an important role. Although the role of the force and velocity factors of the neuromuscular system is poorly understood, it has a strong influence on the maximal anaerobic performance suggesting that the protocol of the MART should be developed in the direction where force and velocity variables could be measured during running. The force-time measurements during the stride might give more information on the development of muscle fatigue within individuals and it might be a more specific way to determine the training intensities of different training zones.

The use of MART for training in high performance athletes requires closer scrutiny, since the effects of different training methods and associated variabilities as well as various training intensities need to be addressed. Further research is also required to establish the utility of submaximal power indices to determine training intensities for different training zones with particular emphasis on reducing their variability. This would be important for sprint coaches and athletes in their daily training.

## 7 CONCLUSIONS

The following conclusions were drawn from the present results:

1. The MART and 30-m speed test with a running start provided a useful and practical test system for the determination of neuromuscular and metabolic components of maximal anaerobic running performance. The regression analyses showed that the results of the MART and 30-m speed test accounted for 87% and 92% of the total variation of the average velocity in the 400-m run and maximal power in the MART, respectively. The present results indicated that the most important determinants of the maximal anaerobic running performance were maximal running velocity ( $V_{30m}$  or  $V_{20m}$ ), sprinting economy ( $P_{10mM}$ ) and anaerobic capacity ( $\Delta P$  or peak BLa).
2. Maximal power increased with the grade of uphill running in the MART. The increased peak blood lactate concentration and oxygen deficit with the increased treadmill inclination suggest that the lactic capacity was not completely used at the grade of  $1^\circ$  and  $4^\circ$ . Consequently, the increased maximal power with the increased inclination resulted from the greater utilisation of anaerobic capacity.
3. The relative proportion of the metabolic components to determine anaerobic work capacity increased and the proportion of force and speed characteristics of the neuromuscular system decreased with the increased treadmill inclination in the MART.
4. The MART is a valid anaerobic test since the maximal power expressed as oxygen demand was 1.4 - 2.6 times the  $VO_{2max}$ , the contribution of anaerobic energy yield ranged from 64% to 68%, the peak blood lactate

concentration was at high level and significant correlations were observed between the results of the MART and Wingate test. Furthermore, sprint and middle distance runners, who were supposed to have a high anaerobic work capacity, attained higher maximal power in the MART than power athletes, long distance runners and untrained subjects.

5. The reliability figures of the MART variables were good enough to make the MART reliable. The repeatability of the MART variables depends on the subjects so that sprint athletes who were accustomed to the anaerobic type of training had higher repeatability figures than untrained subjects.
6. The increased maximal power of the MART during a 10-week sprint training period suggested that MART is a sensitive test method to evaluate training effects in well-trained sprint athletes. Correlation analyses showed that the lower levels of blood lactate vs. running velocity curve could be shifted to higher velocities and peak blood lactate concentration could be decreased when the volume of extensive interval training is high. In addition, bounding exercises influenced the anaerobic work capacity positively. However, the running velocities at higher blood lactate levels were not increased during the sprint training period and they were not related to the volume of any specific training methods.

## 8 YHTEENVETO

Tämän vuosisadan alkupuolelta lähtien tutkijat eri puolella maailmaa ovat kehittäneet erilaisia menetelmiä anaerobisen tehon ja kapasiteetin mittaamiseksi. Toisin kuin aerobisen energiantuoton mittaamiseen anaerobisen energiantuoton mittaamiseen ei ole olemassa yhtä yleisesti hyväksyttyä ja käyttökelpoista testimenetelmää. Anaerobisen energiantuoton mittaamenetelmien ongelmana on, että anaerobiset testimenetelmät mittaavat epäsuorasti anaerobista energiantuottoa. Toinen yhtä suuri ongelma on anaerobisten testimenetelmien käyttökelpoisuus. Testin pitää olla luotettava (reliaabeli) ja pätevä (validi) mittaamaan anaerobista suorituskykyä. Jotta testiä voitaisiin käyttää urheilijoiden testaukseen, testitulosten variaatio ei saisi olla suurempi kuin harjoitteluvaikutus. Varsin usein urheilijat kykenevät itse arvioimaan suorituskykynsä paremmin kuin anaerobiset testit. Lisäksi anaerobisen testin käyttökelpoisuus on kyseenalainen urheilijoille, jos testin ainoa anti on arvio anaerobisesta kapasiteetista tai tehosta: kenttätesti on siinä tapauksessa aivan yhtä käyttökelpoinen.

Tällä hetkellä ei ole olemassa anaerobista testiä, joka antaisi kuvan anaerobisen kapasiteetin ja tehon lisäksi myös muista tärkeistä ominaisuuksista, jotka vaikuttavat anaerobiseen suorituskykyyn. Sen vuoksi tämän tutkimuksen tarkoituksena oli kehittää uusi anaerobinen juoksumattotesti (MART), jonka avulla voitaisiin mitata maksimaalisen anaerobisen kapasiteetin lisäksi siihen vaikuttavia hermo-lihasjärjestelmän voima-nopeus- ja metaboliamuuttujia. Tarkoituksena oli vielä, että MART:ä voitaisiin käyttää hyväksi harjoittelun ohjelmoinnissa anaerobista suorituskykyä vaativissa lajeissa kuten pikajuoksussa.

Tutkimukseen osallistui 27 mies- ja 8 naispuolista 400 m:n juoksijaa, 8 keskimatkojen (800 - 1500 m) ja 11 pitkien matkojen (5000 m - maraton) miesjuoksijaa, 14 miespuolista teholajien urheilijaa (5 pikajuoksijaa, 7 kymmenottelijaa sekä 1 pesäpalloilija ja kolmiloikkaaja) sekä 34 liikunnan mies-

opiskelijaa. Tutkimus koostui mittauskokonaisuuksista, joissa pyrittiin selvittämään (1) erilaisten hermo-lihasjärjestelmän voima-nopeus- ja metabolia-muuttujien merkitystä anaerobista suorituskykyä selittävinä tekijöinä, (2) juoksumaton kulman vaikutusta MART:n tuloksiin, (3) MART:n validiutta ja reliabilisuutta sekä (4) pikajuoksuharjoittelun vaikutusta MART:n tuloksiin.

MART koostui  $n \times 20$  s:n vedoista juoksumatolla palautuksen ollessa 100 s. Testin aikana juoksumaton kulma oli vakio ( $1^\circ$ ,  $3^\circ$ ,  $4^\circ$ ,  $5^\circ$  tai  $7^\circ$ ) mutta juoksu-nopeus lisääntyi jokaisen 20 s:n juoksun jälkeen kunnes koehenkilö väsyi. Ensimmäisen juoksun nopeus valittiin siten, että veren laktaattipitoisuus ei nousisi yli  $3 \text{ mmol} \cdot \text{l}^{-1}$  ja että koehenkilö pystyisi juoksemaan 8 - 12 vetoa. Koska mekaaninen työ on vaikeaa määrittää juoksusta, jokaisen 20 s:n juoksun teho laskettiin hapentarpeena käyttämällä American College of Sports Medicinen (ACSM) kaavaa. Hapentarve ensimmäisessä vedossa oli  $62 - 74 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  ja nopeuden lisäys vetojen välillä vastasi  $6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ :n lisäystä hapentarpeessa. Noin 40 s:a jokaisen vedon jälkeen sekä 2.5 ja 5 min uupumisen jälkeen otettiin sormenpäästä verinäyte veren laktaattipitoisuus vs. juoksunopeus- tai hapentarvekäyrän määrittämiseksi. Lisäksi koehenkilöt tekivät kolme kevennyshyppyä (CMJ) ennen MART:ä sekä heti ja 5 min MART:n jälkeen.

MART:n lopussa juoksumatto ja kello pysäytettiin, kun koehenkilö ei enää pystynyt juoksemaan juoksumaton nopeutta. MART:stä määritettiin maksimaalinen teho ( $P_{\text{max}}$ ), tehot  $10 \text{ mmol} \cdot \text{l}^{-1}$  ( $P_{10\text{mM}}$ ),  $5 \text{ mmol} \cdot \text{l}^{-1}$  ( $P_{5\text{mM}}$ ) ja/tai  $3 \text{ mmol} \cdot \text{l}^{-1}$  ( $P_{3\text{mM}}$ ) laktaattitasoilla, korkein laktaattipitoisuus (peak BLa), kahden parhaan kevennyshypyn painopisteen nousukorkeuden keskiarvo ( $\text{CMJ}_{\text{rest}}$ ) sekä kevennyshypyn heikkeneminen MART:n aikana ( $\text{CMJ}_{\text{decr}}$ ). Muista testeistä määritettiin maksimaalinen hapenottoikyky ( $\text{VO}_{2\text{max}}$ ), maksimaalinen juoksunopeus ( $V_{20\text{m}}$  tai  $V_{30\text{m}}$ ) sekä keskimääräinen juoksunopeus 400 m:llä ( $V_{400\text{m}}$ ). Lisäksi  $P_{\text{max}}$ :n ja  $\text{VO}_{2\text{max}}$ :n erotusta käytettiin anaerobisen kapasiteetin kuvaajana ( $\Delta P$ ).

(1) Anaerobista suorituskykyä kuvaaviksi muuttujiksi valittiin tässä tutkimuksessa MART:ssä määritetty  $P_{\text{max}}$  ja 400 m:n juoksusta laskettu  $V_{400\text{m}}$ . Erilaisten hermo-lihasjärjestelmän voima-nopeus- ja metabolia-muuttujien merkitystä anaerobista suorituskykyä selittävinä tekijöinä tutkittiin vertaamalla  $P_{\text{max}}$ :a ja  $V_{400\text{m}}$ :ä muihin eri testeistä mitattuihin muuttujiin. Tämän tutkimuksen tulokset osoittivat, että MART:ä voidaan käyttää määrittämään anaerobisen suorituskykyyn vaikuttavia voima-nopeus- ja metaboliamuuttujia. MART:n tulokset kuvasivat anaerobista työkapasiteettia ( $P_{\text{max}}$ ), anaerobista kapasiteettia (peak BLa ja  $\Delta P$ ), pikajuoksun taloudellisuutta ( $P_{10\text{mM}}$ ,  $P_{5\text{mM}}$  ja  $P_{3\text{mM}}$ ), hermo-lihasjärjestelmän voima-nopeusominaisuuksia ( $\text{CMJ}_{\text{rest}}$ ) sekä lihasten voimantuottokyvyn heikkenemistä ( $\text{CMJ}_{\text{decr}}$ ). Regressio- ja korrelaatio-analyysien perusteella maksimaalinen juoksunopeus ( $V_{20\text{m}}$  ja  $V_{30\text{m}}$ ), pikajuoksun taloudellisuus ( $P_{10\text{mM}}$ ) ja anaerobinen kapasiteetti (peak BLa ja  $\Delta P$ ) selittävät parhaiten suorituskykyä MART:ssä ja 400 m:n juoksussa.

(2) Juoksumaton kulman vaikutusta MART:n tuloksiin tutkittiin tekemällä MART kolmella eri kulmalla satunnaisessa järjestyksessä:  $1^\circ$  (MART<sub>1</sub>),  $4^\circ$  (MART<sub>4</sub>) ja  $7^\circ$  (MART<sub>7</sub>). Ennen jokaista MART:ä koehenkilöt tekivät kolme

submaksimaalista juoksua kyseisellä kulmalla yksilöllisen hapentarpeen määrittämiseksi. Hapenkulutus mitattiin jokaisen MART:n aikana happivajeen ja anaerobisen energiantuoton määrittämiseksi. Lisäksi koehenkilöt tekivät radalla 20 m:n nopeustestin lentävällä lähdöllä. Tämän tutkimuksen mukaan juoksumaton kulma vaikuttaa  $P_{\max}$ :iin siten, että teho kasvaa kulman kasvaessa 1°:sta 7°:een. Tämä näyttäisi johtuvan siitä, että anaerobisen energiantuoton sekä suhteellinen että absoluuttinen osuus lisääntyy kulman kasvaessa, joten pienillä kulmilla ei ole mahdollista hyödyntää anaerobista kapasiteettiä kokonaan. Korrelaatio- ja regressio-analyysit osoittivatkin, että 1°:een kulmalla juoksunopeus kasvaa niin suureksi, että hermo-lihasjärjestelmän voima-nopeusominaisuudet tulevat  $P_{\max}$ :a rajoittavaksi tekijäksi ja anaerobinen kapasiteetti jää hyödyntämättä. Toisaalta 7°:een kulmalla anaerobisen kapasiteetin merkitys  $P_{\max}$ :n selittäjänä on suuri.

(3) MART:n validiutta tutkittiin mittaamalla aerobista ja anaerobista energiantuottoa MART:n aikana, vertaamalla MART:n tuloksia Wingate polkupyöräergometritestin tuloksiin, vertaamalla MART:n tuloksia erilaisten urheilijaryhmien välillä sekä tutkimalla pikajuoksuharjoittelun vaikutusta MART:n tuloksiin. Tämän tutkimuksen tulokset osoittivat, että MART on validi anaerobinen testimenetelmä. MART:n anaerobinen luonne näkyy  $P_{\max}$ :ssa, peak BLa:ssa ja anaerobisen energiantuoton suhteellisessa osuudessa, sillä  $P_{\max}$  oli 1.4 - 2.6 kertainen  $VO_{2\max}$ :iin nähden ja MART:n jälkeen mitatut veren laktaattipitoisuudet vastasivat 400 m:n juoksun jälkeen mitattuja arvoja. Anaerobisen energiantuoton suhteelliseksi osuudeksi mitattiin 64% - 68%, mikä vastaa noin 60 s:n yhtäjaksoista maksimaalista suoritusta. Merkitsevä positiivinen korrelaatio  $P_{\max}$ :n ja  $V_{400m}$ :n välillä homogeenisellä ryhmällä 400 m:n juoksijoita osoittaa, että MART mittaa anaerobista suorituskykyä juoksussa, sillä 400 m:n juoksu on tunnetusti anaerobinen juoksumatka.

MART:n validiutta osoitti myös se, että 400 m:n ja keskimatkojen juoksijat, joilla oletettavasti on paras anaerobinen työkapasiteetti, saavuttivat suuremman  $P_{\max}$ :n kuin teholajien urheilijat, kestävyysjuoksijat ja liikunnan opiskelijat. Tärkeimpiä anaerobisen suorituskyvyn osatekijöitä verrattaessa havaittiin, että teholajien urheilijoilla ja 400 m:n juoksijoilla oli korkein anaerobinen kapasiteetti (peak BLa ja  $\Delta P$ ) ja teho ( $CMJ_{rest}$ ) ja että 400 m:n ja keskimatkojen juoksijoilla oli paras pikajuoksun taloudellisuus ( $P_{10mM}$ ).

MART:n tuloksia verrattaessa vastaaviin Wingaten polkupyöräergometritestin tuloksiin havaittiin, että neljä seitsemästä korrelaatiosta oli merkitseviä mutta matalia. Tämä tarkoittaa sitä, että nämä kaksi anaerobista testiä mittaavat ainakin osittain samoja ominaisuuksia. Matalat korrelaatiot tarkoittavat, että anaerobisen testin pitäisi olla lajispesifinen, koska anaerobiseen kapasiteettiin vaikuttaa työskentelevien lihasten massa ja anaerobiseen tehoon lihasten supistustapa ja harjoittelu muokkaa anaerobista suorituskykyä lajin vaatimusten mukaisesti.

MART:n reliabilisuus tutkittiin pikajuoksijoilla ja liikunnan opiskelijoilla siten, että koehenkilöt tekivät MART:n kahdesti yhden viikon aikana. MART:n tulosten toistettavuus oli hyvä  $P_{\max}$ :n,  $P_{10mM}$ :n,  $P_{5mM}$ :n ja  $CMJ_{rest}$ :n osalta mutta  $CMJ_{dec}$  oli epätarkka, joten sitä voidaan pitää vain karkeana

väsymyksen mittarina. Tutkimuksen tulokset osoittivat myös, että MART:n tulosten luotettavuus on parempi pikajuoksijoilla kuin liikunnan opiskelijoilla.

(4) Pikajuoksuharjoittelun vaikutusta MART:n tuloksiin tutkittiin tekemällä MART ennen ja jälkeen 10-viikon tehokasta pikajuoksuharjoittelujaksoa, joka ajoittui maaliskokuulle sisä- ja ulkoratakilpailukauden väliin. Samat pikajuoksijat tekivät seuraavan vuoden toukokuussa kontrollina MART:n uudelleen kahdesti vähintään kolmen päivän palautuksella. Kymmenen viikon pikajuoksuharjoittelu kehitti anaerobista työkapasiteettia ( $P_{\max}$ ) 400 m:n juoksijoilla, mutta harjoittelu ei parantanut anaerobista kapasiteettia, pikajuoksun taloudellisuutta tai voima-nopeusomaisuuksia.  $P_{\max}$  muuttui enemmän 10-viikon harjoitusjakson kuin yhden harjoitteluvuoden aikana, mikä osoittaa, että harjoitteleilla pikajuoksijoilla kehittyminen on vähäistä harjoittelemattomiin koehenkilöihin verrattuna. Korrelaatioanalyysi osoitti, että yksilölliset muutokset  $P_{3mM}$ :ssa, peak BLa:ssa, ja  $CMJ_{rest}$ :ssa ovat yhteydessä tiettyjen harjoitusmenetelmien määriin. Sen vuoksi voidaan sanoa, että MART on sensitiivinen testimenetelmä kuvaamaan anaerobisen suorituskyvyn sekä siihen vaikuttavien voima-nopeus- ja metaboliategijöiden muutoksia.

Tämän tutkimuksen yhteenvedona voidaan todeta, että MART on reliabeli ja validi testimenetelmä, jota voidaan käyttää anaerobisen suorituskyvyn ja siihen vaikuttavien voima-nopeus- ja metaboliamuuttujien mittaamiseen pikajuoksijoilla. Juoksumaton kulmalla voidaan säädellä voima-nopeus- ja metaboliategijöiden painoarvoa testissä siten, että pienillä kulmilla voima-nopeustegijät rajoittavat suorituskykyä enemmän kuin metaboliategijät ja suurilla kulmilla metaboliategijöiden painoarvo kasvaa. MART on myös riittävän sensitiivinen testimenetelmä mittaamaan harjoitusvaikutuksia hyvin harjoitteleilla pikajuoksijoilla, joilla muutokset suorituskyvyssä ja sen eri osaluissa yhden harjoitusvuoden tai -jakson aikana ovat pienet.



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