Leena Paavolainen

Neuromuscular Characteristics and Muscle Power as Determinants of Running Performance in Endurance Athletes

With Special Reference to Explosive-strength Training

STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH 63

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Joki tuo rantaan
punaista puuta,
laitat sen rasiaan,
onnea sanoit sen
huomiseen tuovan
ja sait minut uskomaan
- Mikko Kuustonen -

Omistettu perheelleni
Ilkalle, Suville ja Lotalle

ABSTRACT

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Neuromuscular characteristics and muscle power as determinants of running performance in endurance athletes with special reference to explosive-strength training
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The aim of the study was to investigate the importance of neuromuscular characteristics and muscle power as determinants of running performance in endurance athletes. It was hypothesized that the running performance of endurance athletes would improve by training their neuromuscular characteristics, including improvements in muscle power and running economy. A total of 65 male athletes performed a 5-km (5K) or 10-km (10K) time trial and maximal 20-m (V_{20m}) or 30-m (V_{30m}) speed test on an indoor track, and running economy (RE) tests on a treadmill and on the track. Maximal anaerobic (MART) and aerobic treadmill running tests were used to determine maximal velocity in MART (V_{MART}) and maximal oxygen uptake (VO_{2max}). The 10K led to a significant reduction in the neuromuscular characteristics and track VO_{2max} but these fatigue-induced changes did not differentiate between high (HC) and low (LC) caliber athletes. Instead, the mean contact times (CT) of constant velocity laps (CVL) during time trials correlated with V_{10K} and V_{5K}. V_{5K} also correlated with V_{20m}, CTs and stride rates in maximal 20-m run. HC had significantly shorter mean CTs of CVLs than LC. Preactivity of gastrocnemius (GA) in relation to the IEMG of the total contact phase during the CVLs was higher in HC than LC and the relative IEMGs of vastus lateralis in the propulsion phase compared to the IEMG of the maximal 20 m run were lower in HC than LC. The results suggest that ability to produce force rapidly throughout the 5K and 10K accompanied by optimal preactivation and contact phase activation were important for the running performance in endurance athletes. V_{MART} correlated significantly with V_{5K}, peak blood lactate concentration in MART (peak Bla_{MART}), V_{20m} and V_{30m}, and CT in the maximal 20-m run but not with VO_{2max}. Middle distance runners had a significantly higher V_{MART}, V_{30m} and peak Bla_{MART} than triathletes and cross-country skiers further suggesting that V_{MART} is determined by both neuromuscular and anaerobic characteristics and that V_{MART} can be used as a measure of muscle power in endurance athletes. During the 9 weeks of training period the 5K time, RE and V_{MART} improved in experimental group (E) but no changes were observed in control group (C). V_{20m} and 5J increased in E and decreased in C. VO_{2max} increased in C but no changes were observed in E. In the pooled data the changes in the 5K velocity during 9 weeks of training correlated with the changes in RE (VO_2) and V_{MART}. These results showed that simultaneous explosive-strength and endurance training produced a significant improvement in the 5K without changes in VO_{2max}. This improvement was related to improved neuromuscular characteristics which were transferred into improved muscle power and running economy. In conclusion, a hypothetical model for distance running performance in endurance athletes was constructed using the major determinants of performance of the present study: aerobic power, running economy, neuromuscular characteristics and muscle power.

Key words: Distance running performance, endurance athletes, muscle power, neuromuscular characteristics, running economy, aerobic power, explosive-strength training

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Jyväskylässä, 20. päivänä lokakuuta 1999

CONTENTS

LIST OF ORIGINAL ARTICLES

The present study report is based on the results presented in the following papers, which will be referred to by their Roman numerals:

I. Paavolainen, L., Häkkinen, K., Nummela, A., Rusko H. (1999) Treadmill and track running physiological responses as determinants of 10-km running performance. Submitted for publication

II. Paavolainen, L., Nummela, A., Rusko H., Häkkinen, K. (1999) Neuromuscular characteristics and fatigue during 10-km running. Int J Sports Med 20: 1-6.

III. Paavolainen, L., Nummela, A., Rusko H. (1999) Neuromuscular characteristics and muscle power as determinants of 5-km running performance. Med Sci Sports Exerc 31: 124 -130.

IV. Paavolainen, L., Nummela, A., Rusko H. (1999) Muscle power and VO_{2max} as determinants of horizontal and uphill running performance. Submitted for publication

V. Paavolainen, L., Häkkinen, K., Hämäläinen, I., Nummela, A., Rusko H. (1999) Explosive-strength training improves 5-km running time by improving running economy and muscle power. J Appl Physiol 86: 1527-1533.

ABBREVIATIONS AND DEFINITIONS

Anaerobic capacity	maximum amount of ATP resynthesised via anaerobic metabolism (glycolysis) during a short-term maximal exercise
Anaerobic power	rate of ATP resynthesis via anaerobic metabolism(creatine phosphate and glycolysis) during a specific type of short-term maximal exercise
ATP	adenosine triphosphate
Bla	blood lactate concentration
BF	musculus biceps femoris
C	control group
CaO_2	arterial oxygen content
Cardiac output	amount of blood pumped by the heart during a 1-minute period (= heart rate x stroke volume)
Circuit training	specific abdominal and leg exercises with dozens of repetitions without external loads
Coupling-time	transition time between the eccentric and concentric phases in SSC-exercises
CT	ground contact times
CV	coefficient of variation
CVL	constant velocity laps during 5K and 10K
E	experimental group
EMG	electromyographic
Endurance performance	ability to perform a long-term maximal exercise
Explosive strength training	training method which includes rapid muscle actions (e.g. sprint runs and jumping) with low loads
F_EO2	fraction of oxygen in expired air
FT	fast twitch muscle fiber
Fy	horizontal component of the ground reaction force
Fz	vertical component of the ground reaction force
GA	musculus gastrocnemius
Hb	hemoglobin
HC	high caliber endurance runners
LacT	lactate threshold
LC	low caliber endurance runners
MANOVA	multiple analysis of variance
MART	maximal anaerobic running test

Maximal aerobic power	maximum rate of ATP resynthesis via aerobic (oxidative phosphorylation) metabolism
Maximal oxygen uptake	highest value of oxygen uptake measured during incremental test to exhaustion
Mechanical efficiency	amount of work done as a proportion of energy expenditure
Muscle power	ability of the neuromuscular system to produce power during maximal exercise when glycolytic and oxidative energy production is high and muscle contractility may be limited
O_2	oxygen
Oxidative capacity	maximal capacity of muscles to use oxygen depending on their oxidative enzymes levels, fiber-type composition and oxygen availability
Oxidative phosphorylation	ATP synthesize during the transfer of electrons to molecular oxygen
Oxygen demand	estimate of the rate of total energy cost of exercise in oxygen equivalents
PO_2	oxygen pressure
Peripheral diffusion capacity	exchange of oxygen from the capillary to the mitochondria
Pulmonary diffusion capacity	exchange of oxygen from the alveoli to the red blood cells
Q	cardiac output
RCT	respiratory compensation threshold
RE	running economy
Running economy	steady-state VO_2 for a given running velocity
SL	stride length
SR	stride rate
SSC	stretch-shortening cycle
Stroke volume	quantity of blood ejected with each stroke from the heart
ST	slow twitch fibers
Stretch-shortening cycle exercise	eccentric muscular work is followed by the concentric one
SV	stroke volume
$\%SaO_2$	arterial oxygen saturation
Taper training	reduction of volume or intensity of training
V_{20m}	average velocity in the 20-m speed test with a running start on an indoor track
V_{30m}	average velocity in the 30-m speed test with a running start on an indoor track
V_{1200m}	average velocity in 1200 m time trial

V_{5K}	average velocity in 5-km time trial
V_{10K}	average velocity in 10-km time trial
VE	ventilation
V_{MART}	maximal velocity in the MART
V_{max}	maximal velocity in the aerobic power test
VL	musculus vastus lateralis
VO_2	oxygen uptake
VO_{2max}	maximal oxygen uptake
VO_{2max} demand	peak workload during VO_{2max} test
$\%VO_{2max}$	fractional utilization of VO_{2max}
V_{max}	peak velocity during VO_{2max} test
5J	5-jump test
5K	5-km time trial on a 200-m indoor track
10K	10-km time trial on a 200-m indoor track

1 INTRODUCTION

Over the past decades there have been numerous attemps using different methods to determine the running performance in endurance athletes. Since Hill and Lupton (1923) introduced the concept of maximal oxygen uptake (VO_{2max}), one of the most popular beliefs in exercise physiology has been that endurance performance is limited by an inability of the circulatory and respiratory system to provide oxygen at a rate sufficiently fast to fuel energy production by the active muscle mass. Therefore, most of the advanced information has concerned metabolic factors as determinants of endurance performance. However, it has been suggested that, although VO_{2max} is a good predictor of endurance performance in untrained subjects, some other factors such as peak treadmill running performance or running economy, may be better predictors of endurance performance than VO_{2max} in a homogeneous group of well trained elite endurance athletes (e.g. Conley and Krahenbuhl 1980, Powers et al. 1983, Morgan et al. 1989a, Noakes et al. 1990, Billat and Koralsztein 1996). It has also been observed by coaches that some endurance athletes are unable to perform well in a given sport event, although their oxygen transport and utilization capacity is high. This has raised the question of what the athletes should do to further improve their performance capacity.

Although endurance sport events require high aerobic power, athletes must also be able to maintain a relatively high velocity during a race. This emphasizes the role of the neuromuscular characteristics that are related to voluntary and reflex neural activation, muscle force and elasticity (Häkkinen 1994) and running mechanics, as well as the role of anaerobic characteristics, i.e. power and capacity to resynthesize ATP via glycolysis (Green 1994) in elite endurance athletes. Noakes (1988) has suggested that VO_{2max} and endurance performance may not only be limited by central factors related to oxygen uptake, but also by so called peripheral muscle power factors. The neuromuscular and anaerobic characteristics related to muscle power factors have recently been reviewed by Green and Patla (1992) and Liefeldt et al. (1992). However, relatively few studies have investigated the significance of neuromuscular characteristics or muscle power as determinants of endurance performance and only a few methods or tests are available for the measurement of the muscle power in endurance athletes. Rusko and Nummela (1996) have suggested that maximal anaerobic running test (MART) (Rusko et al. 1993) could be used as a measure of muscle power, especially in sprint athletes. They have concluded that peak velocity of the MART (V_{MART}) is influenced both by the anaerobic power and capacity and by neuromuscular characteristics without the influence of VO_{2max}. However, there is a lack of information whether the V_{MART} can be used as a measure of muscle power in endurance athletes.

In well trained endurance athletes who continue their typical endurance-type training for several years, improvement in performance capacity is limited and it is difficult to determine accurately the intensity, type or volume of training that is optimal for each athlete at any given time. Previous training studies (e.g. Hickson et al., 1988, Marcinik et al., 1991, McCarthy et al., 1995) have shown that strength training can improve endurance performance without any changes in VO_{2max}. However, these observations are mainly based on experiments in which heavy resistance strength training has predominated and experimental subjects have been untrained. If previously untrained subjects are used, the changes in performance can easily be attained by almost any method if training intensity sufficiently exceeds the normal level of daily activity. Much less is known about the effects of sport-specific explosive type strength training on endurance performance in well trained endurance athletes and metabolic and neuromuscular adaptations associated with changes in their performance.

The present study was undertaken to examine the importance of neuromuscular characteristics and muscle power as determinants of running performance in endurance athletes. The second purpose of this study was to investigate whether the maximal anaerobic running test (MART) can be used to measure muscle power in endurance athletes. It was also hypothesized that it would be possible to modify the training of endurance athletes so as to improve their running performance by increasing the volume of training for neuromuscular characteristics, and thereby improving their muscle power and running economy.

2 REVIEW OF THE LITERATURE

2.1 Aerobic power and capacity as determinants of endurance performance

It has been hypothesized that endurance performance is influenced by the power and capacity for aerobic muscular activity where different factors (genetic, psychological, environment and state of training) may have a modifying influence into a positive or negative direction (Åstrand and Rodahl 1986). Since Hill and Lupton (1923) measured oxygen consumption during maximal exercise of increasing intensity, most physiologists have understandably believed that the factors related to oxygen transport and utilization are the only determinants of aerobic power and capacity and consequently of endurance performance. It has been suggested that hypoxia develops in the active muscles during exercise and that this hypoxia causes fatigue and thereby limits maximal exercise performance under all conditions. According to many previous studies (e.g. Costill et al. 1973, Davies and Thomson 1979, Foster et al. 1978, Foster 1983, Åstrand and Rodahl 1986, Rowell 1986, Joyner 1991, Bassett and Howley 1997) maximal oxygen uptake (VO_{2max}), a measure of oxygen transport to muscle, sets the upper limit for the performance in endurance exercises. In addition, especially when the population of athletes under investigation have similar VO_{2max} values, submaximal endurance (e.g. Costill et al. 1973, Farrell et al. 1979) and running economy (e.g. Conley and Krahenbuhl 1980, Morgan et al. 1989a) have been shown to be linked to endurance performance. Consequently, Bassett and Howley (1997) have summarized the hypothetical model of the major variables related to VO_{2max} and endurance running performance (Figure 1).

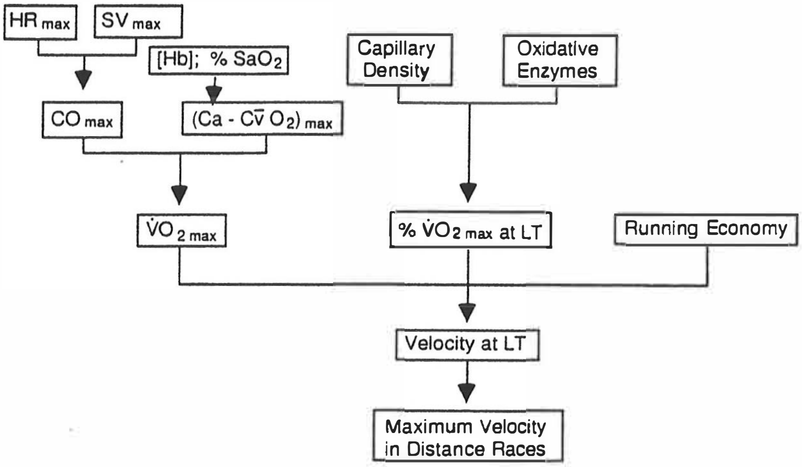


FIGURE 1 Summary of the major variables related to VO_{2max} and the maximal velocity that can be maintained in distance running. From reference Bassett DR and Howley ET (1997) Maximal oxygen uptake: "classical" versus "contemporary" viewpoints. Med Sci Sports Exerc 29: 591- 603, with permission.

2.1.1 VO_{2max}

VO_{2max} may be limited by central and peripheral factors (Rowell 1986, Sutton 1992) (Figure 2). Central oxygen transport depends on maximal cardiac output (Q) and maximal arterial oxygen content (CaO_2). Alterations in blood volume could affect VO_{2max} via changes in Q and stroke volume, and alterations in hemoglobin concentration (Hb) could exert their effect through changes in CaO_2 (Gledhill 1985, Rowell 1986). The peripheral extraction of the delivered oxygen is traditionally expressed as $(a - v)O_2$ difference. Combining central and peripheral factors, there is the circulatory ability to deliver and extract oxygen and VO_{2max} is expressed as the *Fick equation*: $= Q_{max}(a - v)O_{2max}$. With increasing intensities of exercise, the respiratory system may also become a limiting factor in some trained individuals (Dempsey et al. 1984, Sutton 1992).

It has been suggested that the capacity of the central cardiovascular system to transport oxygen to the tissues is the principal determinant of VO_{2max} (Rowell 1986, Bassett and Howley 1997). Elite endurance athletes are characterized by extremely high cardiac output and large stroke volumes

(Ekblom and Hermansen 1968), which are the factors most commonly accounting for different values of VO_{2max} in different individuals (Rowell 1986). The evidence to support this belief comes from studies examining the effects of active muscle mass on VO_{2max}. Many previous studies (e.g. Secher et al. 1974, Bergh et al. 1976, Rowell 1986) have found that VO_{2max} for combined arm and leg work is similar to that measured during leg work alone, suggesting that the central cardiovascular system limits VO_{2max}. On the other hand, Strömme et al. (1977) have suggested that in cross-country skiers VO_{2max} during skiing may be up to 12 % higher than during running. More directly, the evidence implicating a cardiac limitation comes from studies in which direct measurements of cardiac output, leg blood flow and VO_2 were made. It has been concluded that the blood flow to the exercising legs is limited by vasoconstriction when another large group of muscles is simultaneously active and the pumping capacity of the heart is unable to supply the demands of large masses of active muscle and still maintain blood pressure (Secher et al. 1977, Rowell 1986).

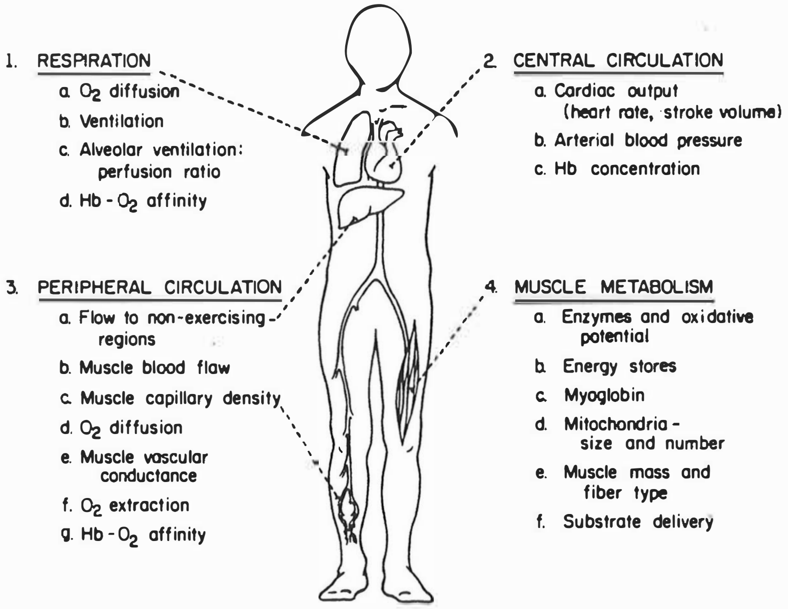


FIGURE 2 Potential physiological factors limiting VO_{2max}. From reference Rowell LB (1986) Human Circulation: Regulation During Physical Stress. New York: Oxford University Press, with permission.

CaO_2 obviously depends on the concentration of Hb and its oxygen binding capacity, the alveolar PO_2, pulmonary diffusion capacity and alveolar ventilation (Rowell 1986). There is usually considerable reserve in the pulmonary system of an average sedentary person (Rowell 1986, Sutton 1992). However, some previous studies (Dempsey et al. 1984, Powers and Williams 1987, Powers et al. 1989, Fuller et al. 1996, Johnson et al. 1996) have identified a group of elite athletes which have developed arterial oxygen desaturation during maximal or heavy submaximal exercise, suggesting that in well trained endurance athletes the respiratory system may limit endurance performance. It has been suggested (Dempsey et al. 1984, Dempsey and Fregosi 1985, Torre-Bueno et al. 1985) that in elite athletes with extremely high maximal cardiac outputs, the high pulmonary blood flow and the decreased transit time of red blood cells in the pulmonary capillary can lead to a pulmonary diffusion limitation. Johnson et al. (1993) have shown that heavy endurance exercise (> 85 % of VO_{2max}) lasting more than 10 min causes diaphragmatic fatigue. Therefore, Johnson et al. (1993, 1996) have suggested that, especially in well trained endurance athletes, respiratory muscle fatigue may also play a role in limiting performance during the heavy endurance exercise. Recently Hopkins et al. (1997) have shown that the integrity of the pulmonary blood-gas barrier in elite athletes is impaired by short-term exercise due to the high capillary pressure that could also be implicated in a compromised central oxygen saturation.

Peripheral diffusion limitation of oxygen between the Hb molecule within red cells of the muscle capillary and the muscle mitochondria is a third possible important determinant of VO_{2max}. For a given level of convective O_2 delivery, it is the muscle O_2 diffusing capacity and myoglobin-facilitated transport through the cytoplasm of the myocyte that limits the rate at which O_2 molecules can flow from the capillary to the mitochondria (Wagner 1991). Endurance training may increase VO_{2max} by increasing muscle blood flow and the overall O_2 diffusing capacity (Wagner 1991). The reason for this is the increased mitochondrial density or increase in capillary surface area for O_2 diffusion resulting from new capillary formation (e.g. Wagner 1991, Segal 1992).

Although VO_{2max} may be a good indicator of aerobic capacity, relatively low correlations have been observed between VO_{2max} and distance running performance in a homogeneous group of well trained endurance athletes (Daniels et al. 1978, Conley and Krahenbuhl 1980, Noakes 1988, Noakes et al. 1990, Morgan et al. 1989a). Furthermore, Noakes (1988,1997,1998) has questioned the old model that hypoxia develops in the active muscles during exercise and that this hypoxia causes fatigue and therefore limits maximal exercise performance under all conditions. The evidence for this criticism is that the plateau phenomenon and oxygen transport as a limiting factor for VO_{2max} (Hill and Lupton 1923, Taylor et al. 1955, Bassett and Howley 1997) have never really been proved (Noakes 1988, 1997, 1998). According to Noakes (1997), skeletal muscle function during endurance exercise appears to be regulated by different mechanisms: 1) to prevent the development of muscle ATP depletion causing irreversible skeletal muscle rigor during high intensity exercise (e.g. Lewis and Haller 1986, Spriet et al. 1987); 2) to prevent cerebral hypoxia during exercise at altitude (e.g. Green et al. 1989, Kayser et al. 1994); 3) to prevent a catastrophic fall in blood pressure (Rowell 1986) that would reduce perfusion of the diseased coronary arteries in chronic heart failure. Therefore Noakes (1988, 1997, 1998) and some other researchers (e.g. Green and Patla 1992, Liefeldt 1992) have suggested that VO_{2max} and endurance performance may not be limited only by central cardiovascular and respiratory factors related to oxygen transport and utilization.

2.1.2 Submaximal endurance

It has been shown that submaximal endurance is strongly dependent on the enhancement of mitochondrial function, oxidative capacity and glycogen stores of skeletal muscles, high percentage of slow twitch fibers in the muscles and increased ability to mobilize fatty acids from adipose tissue and use them as fuel in aerobic metabolism (e.g. Hermansen et al. 1967, Ivy et al. 1980, Rusko et al. 1980, Holloszy and Coyle 1984, Åstrand and Rohdahl 1986, Wells and Pate 1988). The capacity to sustain a high fractional utilization of VO_{2max} (%VO_{2max}) and/or the lactate or respiratory compensation (ventilatory) thresholds as measured in the laboratory have been shown to be good indicators of submaximal endurance capacity (e.g. Costill et al. 1973, Farrell et al. 1979, Aunola and Rusko 1986). Several previous studies (e.g. Costill et al. 1973, Farrell et al. 1979, Kumagai et al. 1982, Powers et al. 1983, Tanaka et al. 1986, Noakes et al. 1990) have found high correlations between submaximal endurance and distance running performance. It has been suggested that if two distance runners have the same VO_{2max}, the one able to perform at a higher percentage of VO_{2max} during the run will have a better chance of maintaining a faster pace and winning the race (Costill et al. 1973). Alternatively, a runner with a lower VO_{2max} than other runners could compensate for this by running at a higher %VO_{2max} to achieve the same performance during a race (Bassett and Howley 1997). However, Kumagai et al. (1982) did not find a significant correlation between fractional utilization of VO_{2max} (%VO_{2max}) and distance running performance. Furthermore, Scrimgeour et al. (1986) reported that %VO_{2max} sustained during a competition was similar in all athlete groups despite their difference in weekly training volumes and different running performance, suggesting that submaximal endurance may not be the only important determinant of endurance performance.

2.2 Running economy as determinant of endurance performance

Running economy, defined as the steady-state VO_2 for a given running velocity, has been shown to correlate highly significantly with endurance running performance, especially in well trained runners who are homogeneous with regard to VO_{2max} and threshold variables (e.g. Conley and Krahenbuhl 1980, Daniels 1985, Morgan et al. 1989a). On the other hand, many studies (e.g. Daniels et al. 1978, Farrell et al. 1979, Noakes et al. 1990) have failed to show any significant relationships between running economy and running performance. These different observations suggest that the relationship between running economy and distance running performance is still controversial. Differences in running economy have been attributed to biomechanical, physiological and neuromuscular adaptations (Andersson 1996). Physiological aspects of running economy are related to body temperature, cardiopulmonary and peripheral factors, muscle fiber type, gender, fatigue and training (Morgan et al. 1989b, Morgan and Craib 1992). Frederick (1991) has suggested that biomechanical mechanisms related to improvements in economy may be associated with the transfer of energy between and within body segments, the excursion of the body's centre of mass or the effective storage and return of elastic energy in tendons and muscles. It has been suggested (Gaesser and Brooks 1984) that the body temperature-related rise in VO_2 is linked to added peripheral blood flow and sweating demands, increased ventilatory rate and a decrease in the efficiency of oxidative phosphorylation. Training-induced reductions in heart rate and ventilation might produce an overall drop in total body VO_2 leading to lower aerobic demands (Bailey and Pate 1991). According to Bosco et al. (1987) a significant correlation observed between the percentage of fast-twitch fibers and VO_2 during submaximal running suggests that slow-twitch fibers may retain stored elastic energy longer without cross-bridge detachement, thus reducing reliance on energy generated from oxidative phosphorylation. Some previous studies (e.g. Conley et al. 1981, 1984, Svedenhag and Sjödin 1985) have reported an improvement in running economy by employing different combinations of distance, interval and uphill training. The reasons for training-induced changes in running economy may be related to better mechanical efficiency, treadmill habituation, alterations in running style and oxidative energy supply and optimization of motor unit recruitment patterns (Morgan and Graib 1992).

2.3 Anaerobic characteristics as determinants of endurance performance

Middle distance runners are a good example of athletes who must be able to maintain rapid velocity throughout a race. To accomplish this a major contribution is necessary from anaerobic power and capacity (Brandon 1995), which are mainly influenced by the rate and capacity of glygolysis and lactic acid production (Green 1994) and the stores and utilization of intracellular phosphates (Hirvonen et al. 1987). Actually, it is also possible that in middle distance running a lower oxygen uptake may be compensated by a greater anaerobic power and capacity (Brandon 1995). Crielaard and Pirnay (1981) compared middle distance (800-3000 m) runners and long distance (10 km - marathon) runners and found that middle distance runners were characterized by a greater anaerobic capacity. They concluded that in distance runners a negative relationship exists between aerobic and anaerobic power. However, both Bulbulian et al. (1986) and Houmard et al. (1991a) have found a significant correlation between anaerobic power variables and distance running (5 - 8.5 km) performance among otherwise well matched (aerobic capacity and running economy) groups of athletes.

Schnabel and Kindermann (1983) observed that a small increase in blood lactate concentration during a non-exhaustive 40-s run is associated with excellent performance in running events. This is in line with the study of Rusko (1993) and Rusko and Nummela (1996) who found that sprinting power at submaximal blood lactate concentration (anaerobic sprinting economy) during the maximal anaerobic running test (MART) may be an important determinant of running performance. 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 anaerobic sprinting economy of a particular athlete. The background of anaerobic sprinting economy includes sprinting technique, the amount of and ability to utilize phosphagen and oxygen stores, muscle lactate production, transport and diffusion of lactate to and removal from blood as well as VO_2 on response (Rusko and Nummela 1996).

These results suggest that although it is well accepted that the major energy contributor to distance running events is the aerobic system, anaerobic characteristics may also be an important determinant of running performance, especially in well trained elite endurance athletes who are homogeneous with regard to their aerobic capacity (Bulbulian et al. 1986, Houmard 1991a).

2.4 Neuromuscular characteristics as determinants of endurance performance

In addition to aerobic and anaerobic components maximal endurance performance may be determined by the neuromuscular characteristics controlling the rate and force of myofibrillar cross-bridge cycle activity (Green and Patla 1992, Noakes 1988). Inside the muscle fibers, sarcolemma and sarcoplasmic reticulum as well as regulatory and contractile proteins could theoretically limit VO_{2max} and maximal endurance performance (Green and Patla 1992). An inability to sustain calcium release from the sarcoplasmic reticulum would lead to lower activation levels and consequently to less force production. On the other hand, a prolongation of time required to remove the calcium from the cytosol would prolong the dissociation of the actin and myosin and result in a delay in the relaxation of the muscle during the recovery phase (Green 1987, Green and Patla 1992, Tate et al. 1991, Metzger 1992, Allen et al. 1992).

2.4.1 Voluntary and reflex neural activation

Force output of muscle contraction is affected by the interaction of muscular, neural and mechanical factors (Komi 1986, Green 1987, Enoka 1988a). The myofibril cross-sectional area is related to maximal muscle strength so that larger muscles, as a result of an increase in fiber size, are able to produce greater force output than muscles with a small cross-sectional area (e.g Ikai and Fukunaga 1968, Sale et al. 1987, MacDougall 1991). Although the maximal force which a muscle can exert is highly related to its cross-sectional area, a poor correlation exists between training-induced increases in strength and muscle size (Enoka

1988a). This dissociation between strength and size occurs because strength performance is determined not only by the quantity of the involved muscles but also by the ability of the nervous system to appropriately activate the muscles (e.g. Enoka 1988a, Sale 1991, Häkkinen 1994). The increased voluntary neural activation of the muscles is usually based on the increases observed in the integrated electromyographic activity (IEMG) suggesting that more motor units have been recruited and/or motor units are firing at higher rates (Enoka 1988a, Sale 1991, Häkkinen 1994). In addition to voluntary neural control, training-induced changes in reflex potention may also take place (Sale et al. 1983, Häkkinen and Komi 1983). The velocity of action, type of action and movement pattern could affect motor unit recruitment within a muscle (Sale 1991). Consequently, neural adaptation is related to increased activation of the prime mover motoneurons, and/or improved co-contraction of synergists, and/or decreased coactivation of the antagonist muscles as reviewed recently by Häkkinen (1994). In this regard, Green and Patla (1992) have hypothesized that neural activation may have a role as a determinant of VO_{2max} and endurance performance. An inability to properly activate the appropriate muscles or a failure in some excitation-contraction process within the recruited fibers could prevent full utilization of available oxygen (Green and Patla 1992).

2.4.2 Muscle elasticity

Enhancement of power output in maximal effort and the efficiency of human performance are also related to elasticity and stretch-reflexes in muscles and tendons (e.g. Dietz et al. 1979, Komi 1984, Enoka 1988b, Komi 1991). It has been suggested (Aura and Komi 1986, Kyröläinen et al. 1991) that the nervous system plays an important role in regulating muscle stiffness and utilization of muscle elasticity during stretch-shortening exercises such as running and jumping in which relatively high contraction velocities are used. The ability of muscles to store and utilize elastic energy depends on the pre-activity of the muscles (e.g. Dietz 1979), the coupling-time, velocity of stretch and muscle stiffness (e.g. Bosco et al. 1981, Enoka 1988b, Komi 1984, Nicol 1991a). The high pre-activation which is preprogrammed from higher centres of the central nervous system (Melvill-Jones and Watt 1971, Moritani et al. 1990) and the reflex potention after the impact phase play a major role by increasing stiffness in muscles and leading to a faster transition from the braking to the propulsion phase (e.g. Dietz et al. 1979, Bosco et al. 1981, Komi 1984, Enoka 1988b). After the short braking phase the recoil of elastic energy during the propulsion phase increases and the improved efficiency could in part come from elastic energy so that lowered muscular activation becomes possible during the propulsion phase (Williams 1985).

2.4.3 Muscle fiber composition

The force-time characteristics of muscle performance differ between subjects with different relative proportions of fast- (FT) and slow- (ST) twitch fibers in their muscles. A several number of studies have demonstrated that endurance athletes have a higher proportion of ST fibers in their active muscle groups than sprint athletes (e.g. Gollnick et al. 1972, Costill et al. 1976). A muscle composed of a greater percentage of FT fibers has a greater muscle strength, a shorter electromechanical delay, a higher contraction velocity and shorter relaxation times compared to ST type muscles (e.g. Tesch and Karlsson 1978, Viitasalo and Komi 1981, Komi 1984). On the other hand, ST fibers have a longer cross-bridge cycle time and may therefore be able to better utilize long and slow stretches (Bosco et al. 1982).

2.4.4 Distance running mechanics

Distance running performance and economy may also be influenced by stride characteristics, kinetics and the kinematics of running. These factors include: velocity, stride length and rate, ground contact times, ground reaction forces, joint and segment angles and movements of the trunk and arms (e.g. Williams 1985, Andersson 1996). Some performance related data suggest that "more skilled" distance runners tend to have longer strides (Dillman 1975) and lower peak ground reaction forces (Williams and Cavanagh 1987) than less skilled runners, although Cavanagh et al. (1977) found that elite distance runners utilized shorter absolute and relative strides than good distance runners. High stride rates and short ground contact times are known to influence sprint running performance (e.g. Mann and Herman 1985, Mero et al. 1992). Cavanagh and Lafortune (1980) and Williams (1985) reported that also in submaximal running contact times and ground reaction forces differ between a rearfoot and a midfoot striker but there have been no consistent findings between the contact times and distance running performance. Consequently, the most relevant biomechanical factors of the distance running in well trained endurance athletes are still unknown, although some relationships between running mechanics, economy and distance running performance have been reported. In fact, some previous studies (Andersson 1996, Williams 1985, Williams and Cavanagh 1987) have suggested that biomechanical performance in distance running is related to a weighted sum of the influences of many kinetics and kinematics variables.

2.4.5 Fatigue-induced changes of the neuromuscular system

An important factor in an endurance athlete's performance is no doubt the neuromuscular system's ability to work in fatigued conditions. The changes in muscle function associated with fatigue may be identified: loss of force or power output, slowing of relaxation, changes in contractile characteristics and alterations in electrical properties, depending on the circumstances of measurements and how the muscle has been fatigued (Edwards 1981, Gibson and Edwards 1985). Fatigue can be peripher related to an impairment of the function of the peripheral nerves, neuromuscular junction transmission, electrical activity of muscle fibers or failure of sarcolemma and sarcoplasmic reticulum in excitation and contraction processes (Edwards 1981, Gibson and Edwards 1985, Green 1987). Central causes of fatigue include motivation, impaired transmission down the spinal cord and impaired recruitment of motor neurons (Asmussen 1979, Edwards 1981, Gibson and Edwards 1985, Green

1987). Repeated stretch-shortening cycles during prolonged (30 min - 3 h) or short-term (maximal jumps and 400 m run) fatiguing exercises lead to acute decreases in force production by reducing neural input to the muscle and the efficiency of the contractile mechanism (Viitasalo et al. 1982, Gollhofer 1987ab, Moritani et al. 1990, Nicol et al. 1991ab, Nummela et al. 1994). Nicol et al. (1991a) found that maximal sprint velocity and ground reaction forces decreased and ground contact times increased after marathon running suggesting a reduced tolerance to stretch load as well as a loss in the recoil characterisctics of the muscles. The failure in stiffness characteristics and longer transition time between the braking and propulsion phases could reduce the storage of elastic energy during the braking phase, because the ability to store and use of elastic energy is affected by the velocity of the prestretch action, the coupling-time, velocity of stretch and muscle stiffness (e.g. Dietz 1979, Bosco et al. 1981, Enoka 1988b, Komi 1984, Nicol 1991a).

Changes in stride characteristics, kinetics and kinematics of running may also take place during distance running (e.g. Elliot and Ackland 1981, Siler and Martin 1991, Williams et al. 1991). Unfortunately, only a few studies have attempted to examine distance running performance in both high and low caliber runners by investigating the changes in neuromuscular characteristics taking place with the onset of fatigue. A major part of the studies that have approached these questions have not used controlled running velocity (e.g. Elliot and Ackland 1981) or the measurements have only been done under laboratory conditions (Siler and Martin 1991) and/or the subjects under investigation have been heterogeneous with regard to their aerobic capacity (e.g. Nicol et al. 1991a, 1991b, Siler and Martin 1991, Williams et al. 1991). Actually, Siler and Martin (1991) have reported that although some individuals may be more sensitive to the effects of distance running fatigue than others, there seem to be no significant differences between fast and slow distance runners in the running pattern with the onset of fatigue. This supports the observations by Williams et al. (1991) that fatigue does not necessarily result in marked changes in kinematics during submaximal distance running.

2.5 Muscle power as determinant of endurance performance

Although endurance sport events require high aerobic power, athletes must also be able to maintain a relatively high velocity over the course of a race. This emphasizes the role of the neuromuscular and anaerobic characteristics in elite endurance athletes. Bulbulian et al. (1986) and Houmard et al. (1991a) have shown that anaerobic characteristics can differentiate well trained endurance athletes from lower level athletes according to their distance running performance. Some "taper" studies (e.g. Shepley et al. 1992, Houmard et al. 1994) have found an improvement in endurance performance without changes in VO_{2max}. Strength training has been shown to improve the endurance performance of previously untrained subjects (e.g. Hickson et al. 1988, Marcinik et al. 1991, McCarthy et al. 1995) and the running economy of female distance runners

(Johnston et al. 1997) without any changes in VO_{2max}, confirming that neuromuscular characteristics may also be important for endurance performance.

Noakes (1988) has suggested that VO_{2max} and endurance performance may not only be limited by central factors related to oxygen uptake, but also by a so called muscle power factor. Muscle power in this regard has not been defined but it seems to be related to neuromuscular and anaerobic characteristics (Noakes 1988, Green and Patla 1992, Liefeldt et al. 1992, Rusko et al. 1993, Rusko and Nummela 1996). In the present study, muscle power is defined as the ability of the neuromuscular system to produce power during maximal exercise when glycolytic and/or oxidative energy production is high and muscle contractility may be limited. Therefore, muscle power is not a physical term but refers to the concept of Noakes (1988). The definition of muscle power is based on previous studies indicating that an increased H+ ion concentration, which is related to the increased blood lactate concentration, may impair the contractile properties of the muscles (e.g. Mainwood and Renaud 1985, Green and Patla 1992). However, relatively few studies have investigated the significance of muscle power as determinant of endurance performance. In contrast to the aerobic system, the muscle power generated that cannot be accounted for by oxygen consumption is a difficult metabolic construct to measure (Rusko and Nummela 1996), and there are no generally accepted methods or tests to measure or evaluate the muscle power in endurance athletes.

It has been shown (e.g. Scrimgeour et al. 1986, Noakes 1988, Noakes et al. 1990, Houmard et al. 1991b, Billat and Koralztain 1996) that peak treadmill running performance (e.g. the peak velocity associated with VO_{2max}; vVO_{2max}) during the maximal aerobic power test on a treadmill is a better indicator of endurance performance in middle- and long-distance running events than VO_{2max} or running economy alone. Furthermore, vVO_{2max} has been used for the prescription of training for distance runners (Billat and Koralztain 1996, Billat et al. 1999). Noakes (1988) has suggested that peak treadmill running velocity could also be used as a measure of muscle power in endurance runners. However, the aerobic processes (e.g. VO_{2max}) are very important for peak treadmill running velocity during the aerobic power test (e.g. Hill and Rowell 1996), although neuromuscular and anaerobic characteristics may also be involved.

Rusko et al. (1993) and Rusko and Nummela (1996) have suggested that peak velocity in the maximal anaerobic running test (V_{MART}) could be used as an indicator of muscle power, especially in sprint runners, because it is influenced both by anaerobic power and capacity and by neuromuscular characteristics but not by VO_{2max}. V_{MART} has been shown to correlate with 100-m, 400-m, 800-m and 1500-m track times and with cross-country ski performance (Rusko et al. 1993, Rusko and Nummela 1996), as well as with maximal accumulated oxygen deficit (Maxwell and Nimmo 1994), maximal blood lactate concentration (peak Bla_{MART}) and maximal 30-m running velocity (e.g. Nummela et al. 1996). Vuorimaa et al. (1996) and Nummela et al. (1996) have further found that sprint runners and middle-distance runners have significantly higher V_{MART} than long-distance runners.

2.6 Effects of strength training on neuromuscular and endurance performance characteristics

Many endurance sport events do not require only a high level of aerobic performance capacity but neuromuscular characteristics may become increasingly important in elite performance as well. However, skeletal muscle adaptation to strength training in comparison to endurance training is very much different. Endurance training enhances the function of the cardiorespiratory system and the oxidative capacity and glycogen stores of the muscles (e.g. Rusko et al. 1978, Holloszy and Coyle 1984, Åstrand and Rohdahl 1986). Heavy resistance strength training results in neural and muscle hypertrofic adaptations which are known to be primarily responsible for improved strength performance (e.g. Moritani and DeVries 1979, Häkkinen et al. 1985, Komi 1986, Bell and Wenger 1992, Häkkinen 1994). Neural factors have been demonstrated to play a major role in strength development, especially during the early stages of strength gain, while a contribution from muscular hypertrophy gradually increases as training proceeds (Moritani and deVries 1979, Häkkinen and Komi 1983, Häkkinen 1994). However, a specific mode of strength training, explosive-type strength training, may lead to specific neural adaptations with the increased rate of activation of the motor units, while muscle hypertrophy usually takes place to a drastically smaller degree than during typical heavy resistance training (Komi et al. 1982, Häkkinen et al. 1985, Sale 1991, Bell and Wenger 1992, Häkkinen 1994, Marks 1996). Figure 3 presents a schematic summary (Häkkinen 1994) of the effects of heavy resistance and explosive-type strength training modes on the neuromuscular system.

In order to induce increases in both aerobic power and neuromuscular characteristics, careful attention must be paid to the proper combination of strength and endurance training. It has been suggested that training simultaneously for strength and endurance may be associated with limited strength development during the later weeks of training but this type of training might not necessarily affect the magnitude of the increase in VO_{2max} (e.g. Hickson et al. 1980, Hickson 1980, Dudley and Djamil 1985, Hunter et al. 1987, Hortobagyi et al. 1991, Bell et al. 1997). On the other hand, Bell et al. (1991) have suggested that conducting strength training prior to endurance training may be beneficial for strength development if strength and endurance training are performed in sequence. These observations are mainly based on experiments in which heavy resistance strength training has predominated and the subjects under investigation have been previously untrained. However, also in endurance athletes proper strength training used simultaneously with endurance training may result in some improvements in their strength and/or power performance without a concomitant reduction in maximal oxygen uptake (Hunter et al. 1987, Paavolainen et al. 1991).

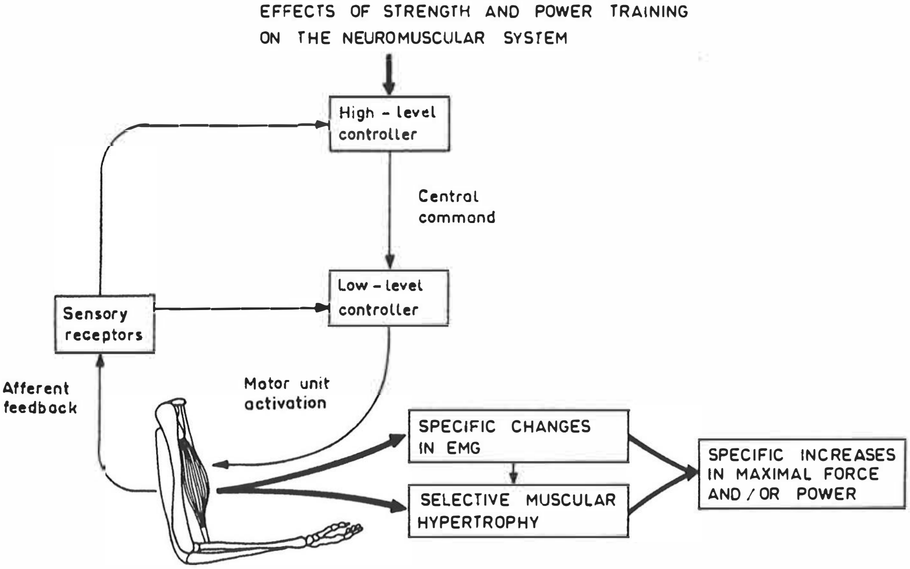


FIGURE 3 Schematic summary of effects of heavy resistance and/or explosive (power) type strength training on the neuromuscular system. From reference Häkkinen K (1994) Neuromuscular adaptation during strength training, aging, detraining, and immobilization. Crit Rev Phys Reh Med 6: 161-198, with permission.

Investigations of strength and endurance training interaction on endurance performance characteristics have received only limited attention. However, it has been shown that, especially in previously untrained subjects, strength training may improve endurance performance without changes in VO_{2max} (e.g. Hickson et al. 1988, Marcinik et al. 1991, McCarthy et al. 1995). The running economy of female distance runners may also be improved by strength training, as reviewed by Johnston et al. (1997). It has been suggested that these improvements may be due to strength training effects on fiber-type recruitment during exercise (Hickson et al. 1988, Marcinik 1991) and/or the neuromuscular response with subsequent alterations in motor unit recruitment patterns (Hickson et al. 1980). Staron et al. (1989) found a decrease in the percent of fast glycolytic type IIB fibers with a concomitant increase in the percent of fast oxidative glycolytic type IIA fibers with strength training. Therefore, one possible explanation for improved performance may also be related to a muscle fiber-type conversion (Staron et al. 1989). During relatively short training periods of some weeks, explosive strength training-induced improvements in force production capacity and performance in endurance athletes might primarily come from neural adaptations without observable muscle hypertrophy (Paavolainen et al. 1991). However, only a limited amount of information is available on the effects of strength training on distance running performance in well trained endurance athletes and metabolic and neuromuscular characteristics associated with changes in their running performance.

3 THE PURPOSE OF THE STUDY

The general purpose of the present series of studies was to investigate the importance of neuromuscular characteristics and muscle power as determinants of running performance in endurance athletes. The maximal anaerobic running test (MART) was used to measure muscle power in the endurance athletes and one purpose of the study was to investigate whether the maximal velocity in MART (V_{MART}) can be used as an indicator of the neuromuscular and anaerobic determinants of running performance in endurance athletes. Finally, it was hypothesized that the training of endurance athletes could be modified in order to improve their distance running performance by paying more attention to training of their neuromuscular characteristics, and thereby improving their muscle power and running economy.

More specifically, the problems of the series of five different studies were as follows:

1. Can peak treadmill running performance be used as a predictor of 5- and 10-km running performance on a track (I, III), and do well trained endurance athletes with different 10-km running performance differ in their treadmill running VO_{2max}, LacT, RCT and economy (I) ?

2. Do fatigue-induced changes in metabolic and neuromuscular characteristics differ between well trained high and low caliber runners who are homogeneous with regard to their aerobic power (I, II) ?

3. Can maximal oxygen uptake on a track differentiate 10-km running performance in a group of well trained endurance athletes having similar uphill maximal oxygen uptake on a treadmill (I) ?

4. What is the importance of neuromuscular characteristics and muscle power as possible determinants of distance track and treadmill running performance in well trained endurance athletes (II, III, IV) ?

5. Does the importance of the muscle power and central factors related to VO_{2max} as determinants of endurance performance differ between horizontal and uphill running (I, IV) ?

6. Can the maximal velocity in MART (V_{MART}) be used as a measure of muscle power in endurance athletes (III, IV) ?

7. Can simultaneous explosive strength and endurance training improve 5-km running performance, aerobic power, running economy, selected neuromuscular characteristics and muscle power in well trained endurance athletes (V) ?

4 MATERIAL AND METHODS

4.1 Subjects and experimental design

A total of 65 male athletes volunteered as subjects for this study. Fourty-two of the subjects were cross-county runners (orienteers), 7 were middle distance runners, 8 triathletes and 8 were cross-county skiers. All the athletes had trained regularly almost daily, from 5 to 25 hours per week and for 6 to 17 years. Aerobic training had predominated the training of the orienteers, triathletes and cross-country skiers prior to the study. The middle distance runners had utilized both aerobic and anaerobic interval training, including various combinations of strength and power training. The basis for the selection of the orienteers in papers I, II, III and V was that their physiological endurance characteristics during an incremental treadmill running test to exhaustion as well as their training background were as homogeneous as possible. The subjects of studies I and II were divided into high caliber runners (HC, n = 10) and low caliber runners (LC, n = 10) according to their velocity in a 10 kilometer time trial (V_{10K}). The HC athletes were more familiar with a track running than the LC athletes. In paper IV it was assumed that due to their different training background the middle distance runners should have higher maximal velocity during horizontal running, better neuromuscular characteristics and anaerobic power and capacity than the triathletes and cross-country skiers. The subjects of study V were divided into experimental (E) and control (C) groups.

Table 1 presents the physical characteristics of the subject groups in each study. Prior to any measurements the subjects were fully notified about the possible risks associated with the study before giving their informed consent to participate in the study. This study was approved by the Ethics Committee of the University of Jyväskylä, Jyväskylä, Finland.

TABLE 1 Mean (± SD) age, height and body weight of the subject groups. HC = high caliber runners (orienteers); LC = low caliber runners (orienteers); E = experimental group (orienteers); C = control group (orienteers); MD = middle distance runners; TR=triathletes; CS = cross-country skiers.

Study/ Subjects (n)	Age (Years)	Height (cm)	Body weight (kg)	Fat (%)
STUDY I, II				
HC (10)	23.8 ± 3.6	178.2 ± 5.1	70.9 ± 4.1	8.0 ± 1.0
LC (10)	24.3 ± 2.8	179.1 ± 4.3	73.9 ± 5.0	9.3 ± 1.0
STUDY III				
Orienteers (17)	24.0 ± 4.0	181.3 ± 5.8	70.6 ± 6.1	9.3 ± 1.9
STUDY IV				
MD (7)	22.1 ± 3.6	180.9 ± 8.2	72.5 ± 9.4	8.6 ± 2.1
TR (8)	27.3 ± 3.8	179.8 ± 3.5	75.4 ± 6.6	9.0 ± 2.2
CS (8)	24.5 ± 2.4	177.5 ± 6.1	73.8 ± 5.6	9.5 ± 2.0
STUDY V				
E (10)	23.3 ± 3.0	179.3 ± 5.3	71.9 ± 4.9	9.5 ± 2.1
C (8)	24.1 ± 5.2	181.5 ± 6.2	70.2 ± 4.2	8.9 ± 1.8

The study consisted of different measurements on a treadmill and on a 200-m indoor track.

(1) In order to measure distance running performance, the subjects ran a 10-km (10K) (I, II) or a 5-km (5K) (III, V) time trial on the track.

(2) In order to examine aerobic power and running economy variables as determinants of distance running performance, the subjects performed a maximal aerobic power test on the treadmill (I, III) and a submaximal running test on a treadmill (I, III) and on the track (III).

(3) In order to investigate neuromuscular characteristics and muscle power as determinants of distance running performance, the subjects performed constant velocity laps during the course of the 5K (III) and 10K (II), maximal 20-m (II, III) and 30-m (IV) speed test on the track and the MART on the treadmill (III, IV).

(4) In order to study fatigue-induced changes in metabolic (I) and neuromuscular (II) characteristics, the subjects performed a 1200-m time trial (I) and a maximal 20-m speed test (II) before and after 10K.

(5) The purpose of studies I and IV was to compare the roles of muscle power and central oxygen uptake factors as determinants of peak running performance between horizontal and uphill running. The subjects performed the MART (IV) and VO_{2max}-test on the uphill treadmill (I, IV) and VO_{2max}-test also on the horizontal track (I) or treadmill (IV). In study IV the tests were done in a random order separated by 1 week.

(6) Study V examined the effects of explosive-strength training on distance running performance so that the subjects were measured before and after 3, 6 and 9 weeks of training. The 5K was performed only before and after 6 and 9 weeks of training.

A chronological presentation of the measurements performed in studies I, II, III and V is given in Tables 2 and 3. The track measurements of study I and II were performed 1-2 weeks after the maximal aerobic power treadmill test. In studies III and V the treadmill measurements were done on the first day and the track measurements on the second day.

TABLE 2 Chronological presentation of the measurements performed on a track (I and II). 20-m = maximal 20-m velocity test, 1200m = 1200-m time trial, 10K = 10-km time trial.

Track measurements						
20-m test	10-min recovery	1200m	15-30 min recovery	10K	20-m test	1200m

TABLE 3 Chronological presentation of the measurements performed on day 1 and 2 (III and V). DT = Dynamometer test, RET = Running economy test, MART = maximal anaerobic running test, 20-m = maximal 20-m velocity test, 5J = 5 forward jumps, 5K = 5 km time trial.

<table>
<tr><td colspan="7">1st day (Treadmill measurements)</td></tr>
<tr><td>DT</td><td>10-min recovery</td><td>RET</td><td>10-min recovery</td><td>Max. aerobic test</td><td>20-min recovery</td><td>MART</td></tr>
<tr><td colspan="7">2nd day (Track measurements)</td></tr>
<tr><td colspan="2">20-m test
5J test</td><td>10-min recovery</td><td>RET</td><td colspan="2">10-min recovery</td><td>5K</td></tr>
</table>

4.2 Maximal aerobic power tests (I, III, IV,V)

The maximal aerobic power tests on the treadmill were incremental tests to exhaustion. In all tests fingertip blood samples were taken after each stage during a 20-s stop of the treadmill between stages to determine blood lactate concentrations (Bla) by an enzymatic-electrode method (EBIO 6666, Eppendorf-Netheler-Hinz GmbH, Germany). The highest blood lactate concentration after the tests (peak Bla) was determined.

In studies I, III and V the initial velocity and inclination were 2.22 $m \bullet s^{-1}$ and 1°, respectively. The velocity was increased by 0.28 $m \bullet s^{-1}$ after every 3-min stage until the velocity of 4.75 $m \bullet s^{-1}$ except that two velocities were increased by 0.56 $m \bullet s^{-1}$ in the middle of the test. After completion of the 3-min stage at 4.75 $m \bullet s^{-1}$, the velocity was kept constant but the inclination was increased every minute by 1° until exhaustion. Ventilation (VE) and VO_2 were measured using the portable telemetric oxygen analyzer (Cosmed K2) for every 30-s period. Subjects breathed through a soft face mask that was connected to a turbine flowmeter. The K2 system was calibrated using room air at the beginning of and immediately after each test.

The LacT (I, V) was determined as O_2 uptake ($ml \bullet kg^{-1} \bullet min^{-1}$) of the stage being just below the point in which blood lactate concentration distinctly increased from its baseline of 1-2 $mmol \bullet 1^{-1}$ (Aunola and Rusko 1986, Ivy et al. 1980), and was verified by using respiratory data (Aunola and Rusko 1986, Wasserman et al. 1973). The RCT (I, III, V) as O_{2m} uptake ($ml \bullet kg^{-1} \bullet min^{-1}$) was determined as being just below the point where F_EO_2 (%) distinctly increased, F_ECO_2 (%) distinctly decreased and the linearity of the VE and VE/VO_2 curve for the second time, after LacT, disappeared (Aunola and Rusko 1986, Paterson and Morton 1986, Simon et al. 1983). The RCT determinations were verified by using a second starting point of accelerated Bla accumulation around 3 $mmol \bullet 1^{-1}$ (Davis et al. 1983). Maximal oxygen uptake (treadmill VO_{2max}) was taken as the highest mean of two consecutive 30-s VO_2 values. Because the inclination of the treadmill was increased and the velocity was kept constant during the last stages of the test, peak treadmill running performance was calculated, not as the peak velocity (vVO_{2max}) but, as the oxygen demand of running during the last min before exhaustion (VO_{2max}demand) using the formula of the American College of Sports Medicine (ACSM 1991):

$VO_2\ (ml \bullet kg^{-1} \bullet min^{-1}) = 0.2 \bullet v(m \bullet min^{-1}) + 0.9 \bullet grade(frac) \bullet v\ (m \bullet min^{-1}) + 3.5$

where v = the speed of the treadmill and grade = the slope of the treadmill expressed as the tangent of the treadmill angle with the horizontal.

In study IV the athletes performed two maximal aerobic power tests on the treadmill - one at a treadmill inclination of 0° and the other at an inclination of 7°. Throughout the tests, metabolic data were collected on a breath-by-breath basis using a SensorMedics 2900Z gas analyzer (SensorMedics, Yorba Linda, USA). Subjects breathed through a mouthpiece that was connected to a two-way breathing valve (Hans Rudolph, Kansas City, USA). At the beginning of and immediately after each test the analyzer was exposed to room air and to known two different gas mixtures: 1) 16 % oxygen and 4 % carbon dioxide 2) 26 % oxygen and 0 % carbon dioxide. VO_{2max} was taken as the highest 60-s VO_2 value ($ml \bullet kg^{-1} \bullet min^{-1}$). Peak treadmill running velocity (V_{max0} and V_{max7}) was taken as the highest speed ($km \bullet h^{-1}$) maintained for 30 s during the horizontal and uphill running, respectively.

4.3 Running economy tests (I, III, IV,V)

In study I, treadmill running economy (RE_{tread}) was measured as steady-state submaximal oxygen uptake (VO_2) during two submaximal runs (3.75 and 4.75 m • s^{-1}) for 5-min duration in the middle of the maximal aerobic power test. In study III, RE_{tread} was measured as a steady-state oxygen uptake during the last min of submaximal 5-min runs at the velocity of 3.67 and 4.17 m • s^{-1}. In study IV, RE_{tread} was determined as a steady-state oxygen uptake during the three 4-min stages in the middle of the horizontal and uphill running tests. In studies III and V, RE_{track} was measured as steady-state VO_2 at the velocities of 3.67 (5 min) and 4.17 (5 min) m • s^{-1}. The velocity of the runs was guided by a lamp speed control system ("light rabbit", Protom, Naakka Inc., Finland). During all treadmill and track runs VO_2 was measured for every 30-s period using a portable telemetric oxygen analyzer (Cosmed K2) (I, III, V) or breath-by-breath using a SensorMedics 2900Z gas analyzer (SensorMedics, Corporation, USA) (IV). RE_{tread} and RE_{track} of each run were calculated as mean VO_2 during the last min of running as unit ml•$kg^{-0.75}$•min^{-1} (Svedenhag 1995) and ml•kg^{-1}•min^{-1}.

4.4 Maximal anaerobic running test (III, IV, V)

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 first run was performed at the velocity of 3.71 m • s^{-1} (III, V) or 4.35 m • s^{-1} (IV) at a 4° (III, V) or 3° (IV) inclination. The velocity of the treadmill was increased by 0.35 m • s^{-1} (III, V) or 0.41 m • s^{-1} (IV) for each consecutive run until exhaustion. This increase in velocity corresponded to a 6 ml • kg^{-1} • min^{-1} increase in the O_2 demand for inclined treadmill running (ACSM 1991). The velocity of the first run as well as the increase in velocity between the runs were selected so that blood lactate concentration would not increase over 3 mmol • l^{-1} after the first run and so that exhaustion would be attained within twelve runs. Exhaustion in the MART was determined as the time when the subject could not longer run at the speed of the treadmill. A harness connected to an emergency brake was used to ensure the safety of the subjects. Maximal velocity (V_{MART}) was determined from the velocity of the last completed 20-s run and from the exhaustion time of the following faster run so that each additional 2 s after 10 s running increased the V_{MART} by 1/6 of the velocity increase between the runs Rusko et al. (1993). Fingertip blood samples were taken at rest, 40 s after each run and 2.5 and 5 min after exhaustion to determine the highest blood lactate concentration in the MART (peak Bla_{MART}). Blood samples were analyzed using the Eppendorf (EBIO 6666) lactate analyzer.

4.5 Track time trials (I, II, III, V)

The subjects ran the 10K (I, II), 5K (III, V) and 1200-m (I) time trials on a 200-m indoor track. The mean velocity of the 5K (V_{5K}) and 10K (V_{10K}) was measured. Before (1200_{pre}) and 1 minute after (1200_{post}) the 10K the subjects performed a 1200 m time trial on the track to determine track velocity (V_{1200}), maximal oxygen uptake (VO_{2peak}) and maximal ventilation (VE_{peak}). There was at least a 15-minute break between the 1200_{pre} and 10K and the criterion for starting the 10K was set to the blood lactate concentration of 2 mmol • l^{-1}.

In all the track time trials VO_2 and VE were measured for each 30-s period using the portable telemetric oxygen uptake analyser (Cosmed K2). Track VO_{2peak} during the 1200-m time trials was taken as the highest 60 s VO_2 value. Fingertip blood samples for the determination of lactate concentration in studies I and II were taken at rest, immediately after the 1200_{pre} and 10K, and 1, 3 and 5 min after the 1200_{post}. In studies III and V blood samples were taken at rest, at the end of the 5K and at 1, 3 and 5 min after exhaustion.

In order to compare force and stride parameters of different athletes during the 5K and 10K, the subjects performed 200 m constant velocity lap (CVL) (4.55 m • s^{-1}) 5 times during the course of the 10K (at start, 3, 5, 7 and 9 km) and 3 times during the course of the 5 K (at start, 2.5 and 4 km). The velocities of the CVL runs were guided by a lamp speed control system ("light rabbit", Protom, Naakka Inc., Finland).

4.6 Maximal velocity and jump tests (II - V)

The V_{20m} (II, III, V) and V_{30m} (IV) tests were run three to four times with a running start of 30m. The running time was measured by two photocell gates (Newtest Inc., Oulu, Finland) connected to an electronic timer and the highest velocity of runs was taken as the results. In the 5J (V) the subjects started from the standing position and tried to cover the longest distance by performing a series of 5 forward jumps with alternative left and right leg contacts. The distance of the 5J were measured with a tape.

4.7 Force and EMG measurements and data analyses (II ,III,V)

The subjects ran the V_{20m} tests and CVLs of the 10K and 5K over a special 9.4-m long force platform system, which consisted of five two-dimensional (2D) and three three-dimensional (3D) force plates (0.9 • 1.0 m each, TR Testi Inc., Finland, natural frequency in the vertical direction 170 Hz) and one 3D force platform (0.9 • 0.9 m, Honeycomb, Kistler, Switzerland, natural frequency in the vertical direction 400 Hz) connected in series and covered with a tartan mat. Each force plate registered both vertical (Fz) and horizontal (Fy) components of the ground reaction force. For further analysis Fz and Fy were recorded by a microcomputer (Toshiba T3200 SX) using an AT Codas A/D converter card (Dataq Instruments, Inc., Ohio) with a sampling frequency of 500 Hz.

Each maximal 20-m run and CVLs included 2-4 ground phases of the right leg on the force platform system. Two successful contacts were averaged and taken as the final result. The horizontal force-time curve was used to separate both Fz and Fy force components into the braking and the propulsion phases (Mero et al. 1992). The integrals of both force-time curves were calculated and divided by the respective time period to obtain the average force for the whole contact phase and for the braking and propulsion phases, separately.

In study II electromyographic (EMG) activity from the m. vastus lateralis (VL), m. rectus femoris (RF), m. biceps femoris (BF) and m. lateral gastrocnemius (GA) of the right leg was recorded bipolarly (Beckman miniature skin electrodes with an inter-electrode distance of 20 mm). The skin area was dry shaved, rubbed with sandpaper and cleaned with alcohol. The electrodes were positioned longitudinally on the belly of the muscle and carefully taped. The EMG signals were amplified and recorded telemetrically (Glonner Biomes 2000) simultaneously with force signals by the microcomputer (Toshiba T3200 SX) using an AT Codas A/D converter card (Dataq Instruments, Inc., Ohio).

The nonsmoothed EMG signals were fullwave rectified, integrated (IEMG), averaged and time normalized for four different phases: 1) pre-activation from 100-0 ms before ground contact 2) ground contact 3) braking phase and 4) propulsion phase. The EMG measurements of the RF during the CVLs and in the $20m_{after}$ were successful only for 11 of the 19 subjects and the remaining three muscles (VL, BF, GA) were taken for the final analysis.

In study V maximal isometric force of the leg extensor muscles was measured by an electromechanical dynamometer (Häkkinen and Komi 1986). Three to five maximal testing contractions were performed at knee and hip angles of 110°. The force (N) in each contraction was recorded by a microcomputer (Toshiba T3200 SX) using an AT Codas A/D converter card (Dataq Instruments, Inc.). The highest force recording was taken for the further analyses.

4.8 Simultaneous explosive-strength and endurance training (V)

In the training study the experimental period lasted for 9 weeks and was carried out in the autumn. The total training volume was the same in both the E and C groups (8.4 ± 1.7 h and 9 ± 2 times per week and 9.2 ± 1.9 h and 8 ± 2 times per week, respectively) but in the E group 32 % and in the C group 3 % of training hours were replaced by sport-specific explosive-strength training including sprinting. The rest of the training in both groups was endurance training and circuit-type training (Fig. 4). The explosive strength training sessions lasted for 15 - 90 min and consisted of various sprints (5 - 10) • (20 - 100 m) and jumping exercises (alternative jumps, bilateral countermovement, drop and hurdle jumps and one-legged five jumps) without additional weight or with the barbell on the shoulders, and of leg press and knee extensor/flexor exercises with low loads but high or maximal movement velocities. The load in the exercises ranged between 0% to 40 % of 1RM. Endurance training in both groups consisted of cross-country or road running for 0.5 - 2.0 h at an intensity below (84 %) or above (16 %) the individual lactate threshold. Circuit training consisted of specific abdominal and leg exercises with dozens of repetitions at slow movement velocity and without any external load.

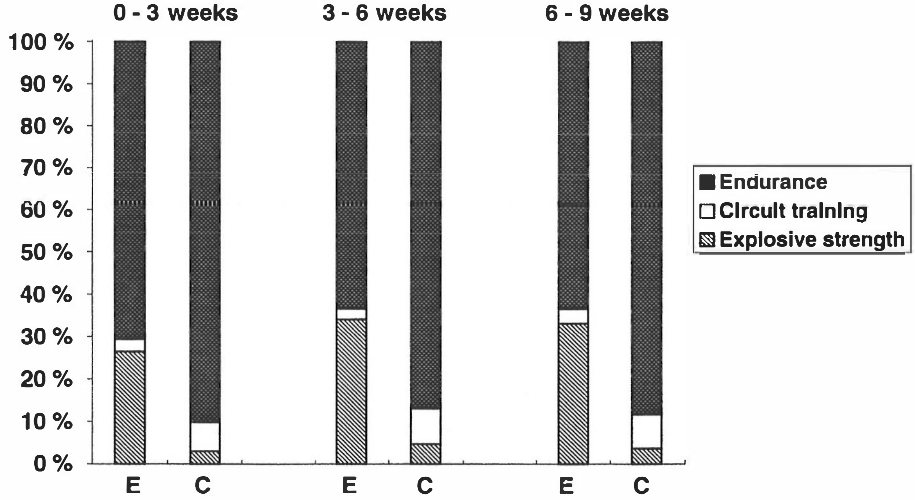


FIGURE 4 The relative volumes of the different training modes in the experimental and control groups during a 9-week training period.

4.9 Statistical methods

Statistical comparisons and analysis were done by the SPSSWIN 6.1.3 programe (SPSS Inc., USA). Means, standard deviations (SD) and coefficients of variation (CV) were calculated by standard methods. Pearson correlation coefficients were calculated to evaluate the relationships between the variables. In study III, a stepwise multiple linear regression analysis was used to predict 5K and treadmill running performance. The independent variables which correlated significantly with the V_{5K} and VO_{2max}demand were entered into a stepwise procedure to select the variables that best predicted the average velocity of 5K and VO_{2max}demand.

The statistical significances ($p < 0.05$ *, $p < 0.01$ **, $p < 0.001$ ***) between and within the high (HC) and low (LC) caliber athletes were tested by a multiple analysis of variance (MANOVA) for repeated measures (I, II) and Student's t-test (paired and unpaired) (I).

In study IV the differences between the horizontal and uphill running tests were tested by Student's t-test. The results of the MART, V_{30m} test, horizontal and uphill running tests in different groups were compared using a one-way analysis of variance and the Scheffe post hoc test.

The MANOVA was also used to evaluate the response to explosive strength training (V). The significance of the changes between the pre to 3-, 6- and 9-week test results and the differences between the experimental and control groups (group by training interaction) were calculated by MANOVA. Because of slight initial group differences, analysis of covariance (ANCOVA) using the pre-test values as the covariate was employed to determine significant differences between the post-test adjusted means of the E group and those of the C group. When a significant F-ratio occurred for the main effects, profile analysis was carried out by MANOVA to locate the source of the difference. The Pearson correlation coefficients were used to evaluate the relationships between the measured variables.

5 RESULTS

5.1 Determinants of distance running performance (I, II, III, IV)

5.1.1 Aerobic power and running economy variables (I, III)

As shown in Table 4 the subjects in studies I and III were relatively homogeneous with regard to VO_{2max}, threshold variables and running economy. They were also closely clustered in their track running (running time for the 5K and 10K) and treadmill running (VO_{2max}demand) performance (Table 4). The correlation coefficients between aerobic power, running economy and performance characteristics in the track and treadmill tests are seen in Table 5. VO_{2max}demand correlated highly significantly ($p < 0.001$) with the V_{5K} and V_{10K}. Both V_{5K} and VO_{2max}demand correlated ($p < 0.05$) with VO_{2max}, RCT, RE_{tread} and RE_{track}. VO_{2max}, LacT and RCT also correlated ($p < 0.01$) with V_{10K} but no significant correlation was found between V_{10K} and RE_{tread} (Table 5). Peak Bla_{tread}, Bla_{5K} or Bla_{10K} did not correlate with the V_{5K} or V_{10K}. The VO_{2max}demand differed significantly between the high caliber (HC) and low caliber (LC) runners (74.3 ± 2.4 and 70.9 ± 0.9 $ml \bullet kg^{-1} \bullet min^{-1}$, $p < 0.01$, respectively), but no significant differences between HC and LC were observed in treadmill VO_{2max}, LacT, RCT, peak Bla_{tread} or RE_{tread} (Table 6).

TABLE 4 Mean, standard deviation and coefficients of variation (CV) of performance characteristics during the track and treadmill tests. VO_{2max}demand = Peak treadmill running performance expressed as the oxygen demand of running during the last min before exhaustion, VO_{2max} = maximal oxygen uptake, LacT = lactate threshold, RCT = respiratory compensation threshold, RE = running economy.

	Study I (n = 20)		Study III (n = 17)	
	Mean ± SD	CV	Mean ± SD	CV
10 km time (min)	37.5 ± 1.9	5.1 %	-	-
5 km time (min)	-	-	18.0 ± 0.7	3.9 %
VO_{2max}demand (ml•kg^{-1}•min^{-1})	72.6 ± 2.5	3.4 %	67.8 ± 2.6	3.8 %
VO_{2max} (ml•kg^{-1}•min^{-1})	68.5 ± 4.3	6.3 %	64.0 ± 2.2	3.4 %
LacT (m•s^{-1})	3.61 ± 0.17	4.7 %	-	-
RCT (m•s^{-1})	4.44 ± 0.22	5.0 %	4.19 ± 0.20	4.8 %
RE_{tread1} (ml•kg$^{-0.75}$•min^{-1})	47.8 ± 2.9	6.1 %	50.0 ± 3.4	6.8 %
RE_{tread2} (ml•kg$^{-0.75}$•min^{-1})	61.3 ± 2.7	4.4 %	56.7 ± 3.0	5.3 %
RE_{track1} (ml•kg$^{-0.75}$•min^{-1})	-	-	44.9 ± 3.2	7.1 %
RE_{track2} (ml•kg$^{-0.75}$•min^{-1})	-	-	51.9 ± 3.1	6.0 %

TABLE 5 Correlation coefficients between the distance running as well as treadmill running performance characteristics. V_{5K} = mean velocity of the 5-km time trial, V_{10K} = mean velocity of the 10-km time trial, VO_{2max}demand = Peak treadmill running performance expressed as the oxygen demand of running during the last min before exhaustion, RE = running economy, VO_{2max} = treadmill maximal oxygen uptake, LacT = lactate threshold, RCT = respiratory compensation threshold. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

	V_{5K}	V_{10K}	RE_{track2}	RE_{tread2}	VO_{2max}	LacT	RCT
V_{5K}	1.00	-	-0.69 **	-0.53 *	0.56 *	-	0.74 ***
V_{10K}	-	1.00	-	ns.	0.69 **	0.76 ***	0.66 **
VO_{2max}demand (I)	-	0.79 ***	-	-0.47 *	0.63 **	0.88 ***	0.78 ***
VO_{2max}demand (III)	0.78 ***	-	-0.66 **	-0.57 *	0.57 *	-	0.73 **

TABLE 6 Aerobic power and economy variables of the treadmill running tests in endurance athletes (HC = high caliber and LC = low caliber). Values are expressed as means ± SD. VO_{2max} = maximal oxygen uptake, Bla = peak blood lactate concentration, RCT = respiratory compensation threshold, LacT = lactate threshold, RE = running economy.

	10 km time (min)	VO_{2max} ($ml \bullet kg^{-1} \bullet min^{-1}$)	Bla ($mmol \bullet l^{-1}$)	RCT ($ml \bullet kg^{-1} \bullet min^{-1}$)	LacT ($ml \bullet kg^{-1} \bullet min^{-1}$)	RE_{tread1} ($ml \bullet kg^{-1} \bullet min^{-1}$)	RE_{tread2} ($ml \bullet kg^{-1} \bullet min^{-1}$)
HC	36.3 ± 1.2	69.7 ± 5.3	11.9 ± 1.6	57.0 ± 4.6	47.1 ± 3.9	48.5 ± 3.3	61.6 ± 2.9
LC	39.2 ± 2.0	67.2 ± 2.8	11.7 ± 1.9	54.9 ± 3.3	44.6 ± 3.7	47.2 ± 2.4	61.2 ± 2.6
HC vs LC	$p < 0.001$	ns.	ns.	ns.	ns.	ns.	ns.

5.1.2 Neuromuscular characteristics and V_{MART} (II, III)

Both V_{5K} and VO_{2max}demand correlated with V_{MART} (Table 7). The V_{5K} also correlated with V_{20m}, CTs in the maximal 20-m run, mean CTs of constant velocity laps during the 5K and with stride rates in the maximal 20-m run. A significant correlation was also observed between V_{10K} and mean CTs of constant velocity laps during the 10K (Table 7). Both V_{5K} and V_{20m} correlated with the duration of the ground contact braking phase in the maximal 20-m run ($r = -0.54$, $p<0.05$ and $r = -0.62$, $p<0.01$, respectively). No correlations were observed between the V_{5K} and ground reaction forces of maximal 20-m run or CVLs. V_{MART} correlated with peak Bla_{MART}, V_{20m} and CTs in the maximal 20-m run (Table 7). No correlation was observed between V_{MART} and VO_{2max}. RE_{track2} correlated significantly with the mean CTs of CVLs during the 5K (Table 7). Examples based on individual data from study III are presented in the appendices 1-3.

The stepwise multiple regression analysis using either the V_{5K} or VO_{2max}demand as the dependent variable showed that the combination of RCT, RE_{track2} and V_{MART} as independent variables accounted for 85 % of the variance in V_{5K} ($p < 0.01$), while RCT and RE_{tread2} accounted for 83 % of the variance in VO_{2max}demand ($p < 0.01$). The other variables did not contribute additional predictive value.

TABLE 7 Correlation coefficients for the selected neuromuscular and muscle power variables and the distance and treadmill running performance. V_{MART} = Maximal velocity of the maximal anaerobic running test, Bla_{MART} = Peak blood lactate concentration in the MART, V_{20m} = Maximal 20 m run velocity, CT = contact times, SR = stride rates, Bf = braking phase of the ground contact, CT_{5K} and CT_{10K} = contact times of constant velocity lap during 5K and 10K, RE_{track2} = track running economy. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	V_{MART}	Bla_{MART}	V_{20m}	CT_{20m}	SR_{20m}	Bf_{20m}	CT_{5K}	CT_{10K}
V_{5K}	0.68 **	ns.	0.63 **	-0.49 *	0.58 *	-0.54 *	-0.50 *	-
VO_{2max}demand	0.54 *	ns.	ns.	ns.	ns.	Ns.	ns.	-
V_{MART}	1.00	0.59 *	0.87 ***	-0.61 **	ns.	Ns.	ns.	-
RE_{track2}	-0.62 **	ns.	ns.	ns.	ns.	Ns.	0.64 ***	-
V_{10K}	-	-	-	-	-	-	-	-0.56 *

During the CVLs of 10K, the high caliber runners (HC) had significantly shorter mean total contact times as well as braking and propulsion phases than the low caliber runners (LC) (Fig. 5A). When the pre-activity of the three measured muscles was expressed in relative values (calculated from the IEMG - activity of the total contact phase in the average CVLs), HC had significantly higher preactivity of the GA than LC (Fig. 5B), while no differences were found in the BF or VL. The relative IEMG values of the VL and GA in the propulsion phase compared to the IEMG - activity of the maximal $20m_{before}$ (in the propulsion phase) were significantly lower in the HC than LC group (Fig. 5B).

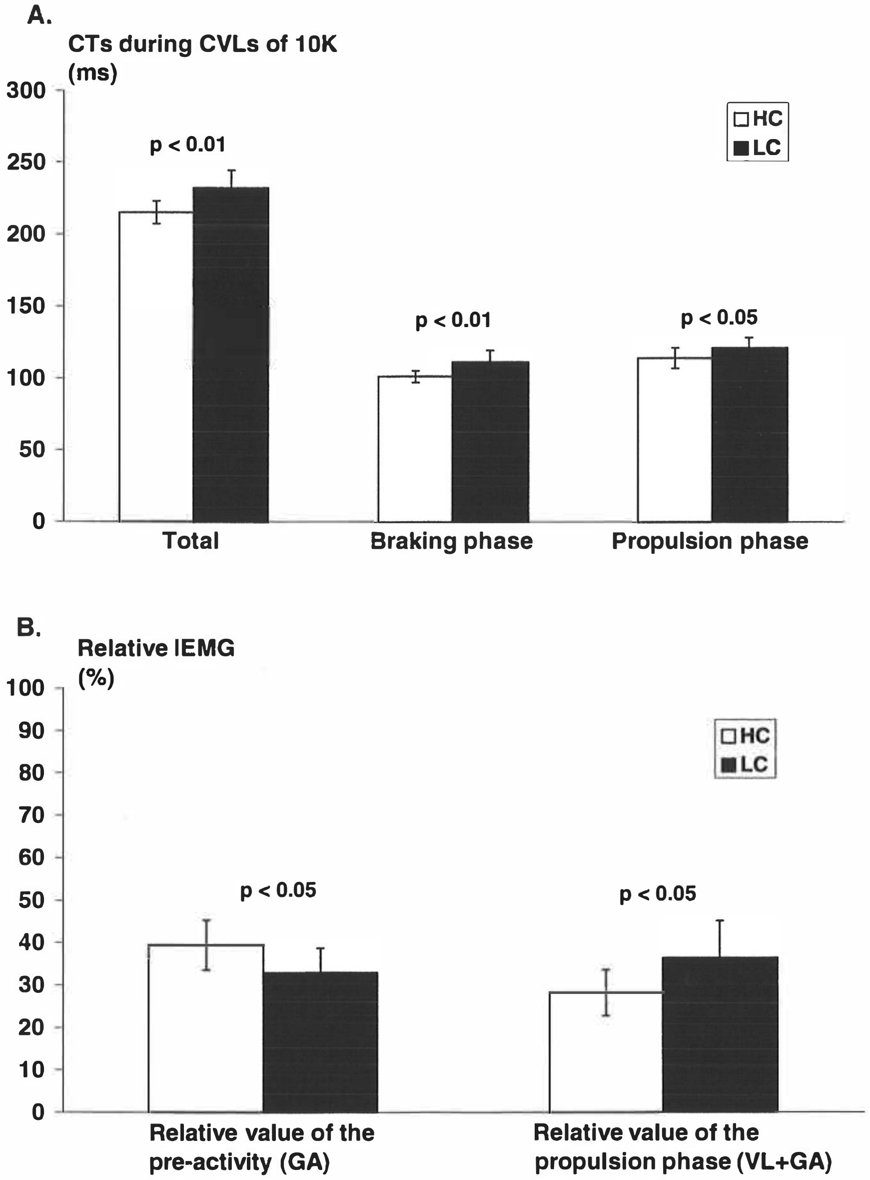


FIGURE 5 The mean total, braking and propulsion phases of the contact times (CT) during the constant velocity laps (CVL) of 10 km time trial **(A)** and the relative values of the preactivity of muscle gastrocnemius (GA) calculated from the average integrated electromyographic (IEMG) activity of the total contact phase in the average constant velocity laps and the relative IEMG values of the vastus lateralis (VL) and GA in the propulsion phase during the constant velocity laps compared to the IEMG-activity of the maximal 20-m run propulsion phase before the 10-km time trial **(B)**. HC = high caliber runners, n = 9; LC = low caliber runners, n = 10.

During the CVLs of 10K the average horizontal ground reaction forces were significantly ($p < 0.05$) lower in HC than LC (157.4 ± 11.8 and 177.5 ± 21.2 N, respectively). However, no significant differences were observed in the ground reaction forces in the units of body weight between the two groups.

5.2 Neuromuscular and metabolic characteristics during horizontal and uphill running (I, IV)

In study I uphill treadmill running VO_{2max} (68.5 ± 4.3 $ml \bullet kg^{-1} \bullet min^{-1}$) and VE_{max} (163.3 ± 14.1 $l \bullet min^{-1}$) were significantly higher ($p < 0.01$) than horizontal track maximal oxygen uptake (VO_{2peak}) (64.2 ± 4.4 $ml \bullet kg^{-1} \bullet min^{-1}$) and VE_{peak} (152.6 ± 12.1 $l \bullet min^{-1}$) . The differences between treadmill VO_{2max} and track VO_{2peak} (VO_{2max} - VO_{2peak}) and treadmill VE_{max} and track VE_{peak} (VE_{max} - VE_{peak}) were significantly smaller in HC than LC (Fig. 6). In the pooled data, as shown in Figure 7A and 7B, V_{10K} correlated ($p < 0.05$) with the differences between treadmill VO_{2max} and track VO_{2peak} ($r = -0.47$) as well as with the differences between treadmill VE_{max} and track VE_{peak} ($r = -0.55$).

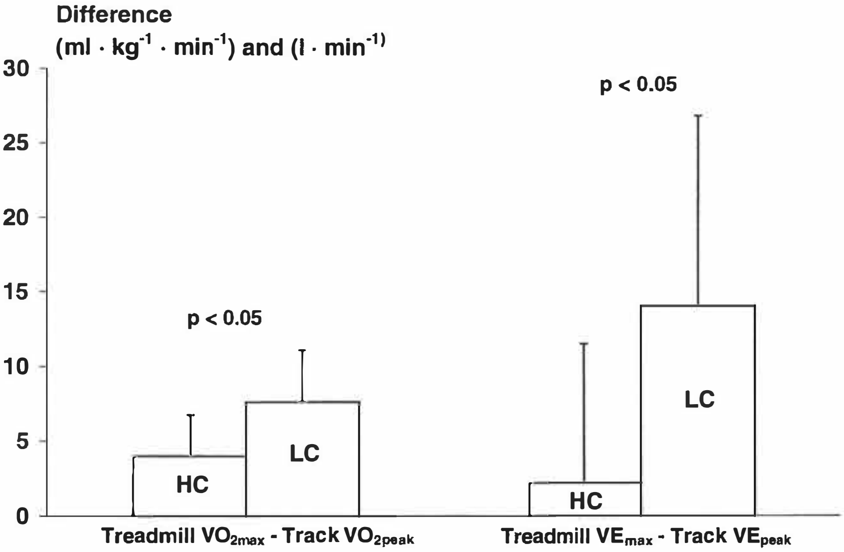


FIGURE 6 Differences between treadmill VO_{2max} and track VO_{2peak} (VO_{2max} - VO_{2peak}) and treadmill VE_{max} and track VE_{peak} (VE_{max} - VE_{peak}). HC = high caliber, n =10 and LC = low caliber, n = 10. * $p < 0.05$

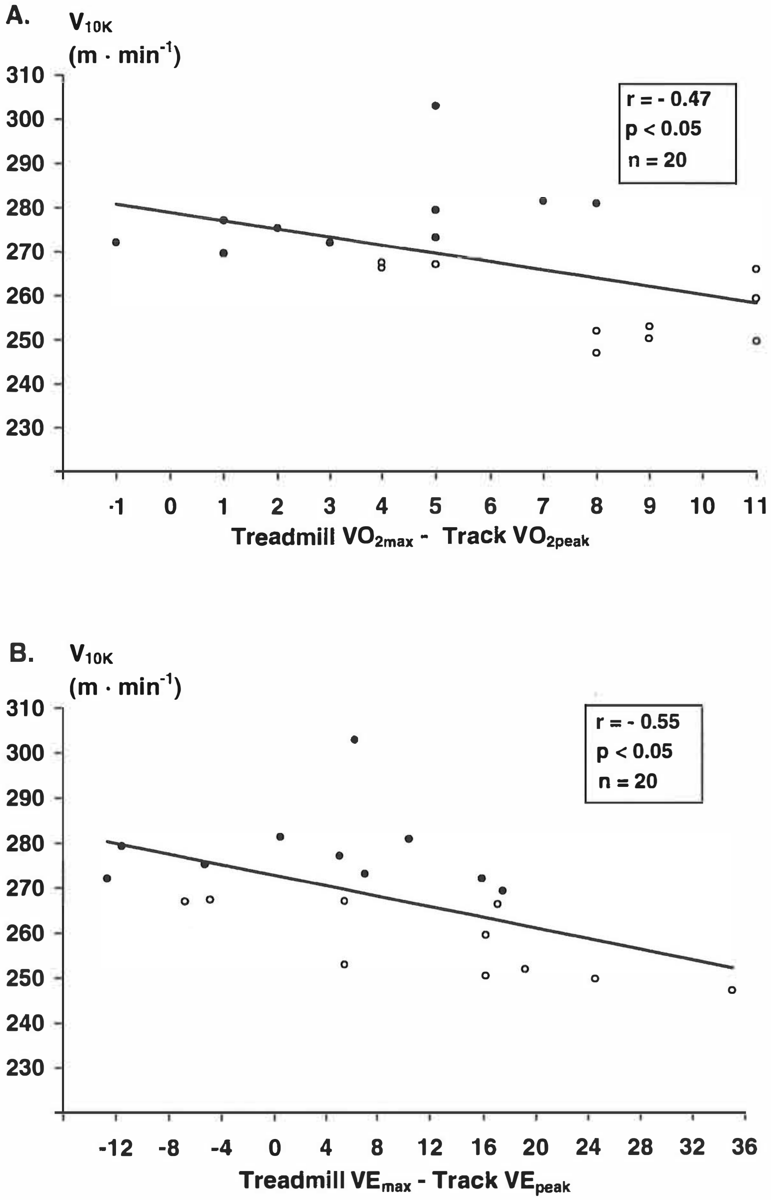


FIGURE 7 Relationship between the velocity of the 10 km time trial and difference between treadmill VO_{2max} and track VO_{2peak} (VO_{2max} - VO_{2peak}) **(A)** and difference between treadmill VE_{max} and track VE_{peak} (VE_{max} - VE_{peak}) **(B)** . ● = HC, O = LC (HC = high caliber, n = 10 and LC = low caliber, n = 10)

In study IV the subjects reached significantly higher V_{max} but lower maximal values for VO_2, ventilation and blood lactate concentration during the horizontal than during the uphill running test (Table 8).

TABLE 8 The maximal values (mean ± SD) measured during the maximal aerobic power tests at the treadmill inclinations of 0° (horizontal) and 7° (uphill). V_{max} = peak treadmill running velocity, VO_{2max} = maximal oxygen uptake, VE_{max} = maximal ventilation, Bla_{max} = peak blood lactate concentration.

Variable	Horizontal	Uphill	p - value
Duration (min)	21.5 ± 1.1	21.1 ± 2.4	ns.
V_{max} ($m \bullet s^{-1}$)	6.08 ± 0.53	3.89 ± 0.50	< 0.001
VO_{2max} ($ml \bullet kg^{-1} \bullet min^{-1}$)	61.4 ± 3.3	65.1 ± 4.0	< 0.001
VE_{max} ($l \bullet min^{-1}$)	130.0 ± 14.8	137.1 ± 16.5	< 0.01
Bla_{max} ($mmol \bullet l^{-1}$)	11.0 ± 2.4	11.8 ± 2.2	< 0.01

The middle distance runners had significantly higher V_{MART}, peak Bla_{MART} and V_{30m} as well as significantly higher V_{max0} and peak Bla_{max0} than the triathletes or cross-country skiers. No significant differences were observed between the triathletes and skiers. No significant differences were found in VO_{2max0}, VO_{2max7}, V_{max7} or in the running economy variables between the three groups (Table 9).

TABLE 9 The maximal values (mean ± SD) measured during the maximal 30 m velocity (V_{30m}) test on a track, the maximal anaerobic running test (MART) on a treadmill and the maximal aerobic power tests at the treadmill inclinations of 0° and 7° (subscripts 0 and 7). V_{MART} = maximal velocity in the MART, V_{max} = peak treadmill running velocity, VO_{2max} = maximal oxygen uptake, Bla_{max} and Bla_{MART} = peak blood lactate concentration.

Variable	Middle-dist. runners	Triathletes	Cross-country skiers	ANOVA
V_{MART} ($m \bullet s^{-1}$)	7.8 ± 0.2	6.8 ± 0.3	7.0 ± 0.2	$p < 0.001$
Bla_{MART} ($mmol \bullet l^{-1}$)	16.4 ± 2.5	11.4 ± 1.7	10.8 ± 1.2	$p < 0.001$
V_{30m} ($m \bullet s^{-1}$)	9.1 ± 0.3	7.9 ± 0.4	8.2 ± 0.3	$p < 0.001$
V_{max0} ($m \bullet s^{-1}$)	6.6 ± 0.3	5.7 ± 0.5	6.0 ± 0.3	$p < 0.001$
VO_{2max0}($ml \bullet kg^{-1} \bullet min^{-1}$)	61.5 ± 3.5	60.5 ± 3.0	63.2 ± 2.3	ns.
Bla_{max0} ($mmol \bullet l^{-1}$)	13.5 ± 1.6	9.5 ± 1.9	10.5 ± 1.8	$p < 0.01$
V_{max7} ($m \bullet s^{-1}$)	4.3 ± 0.3	3.8 ± 0.6	4.0 ± 0.2	ns.
VO_{2max7}($ml \bullet kg^{-1} \bullet min^{-1}$)	66.9 ± 3.7	63.4 ± 4.8	65.3 ± 2.9	ns.
Bla_{max7} ($mmol \bullet l^{-1}$)	13.8 ± 1.2	10.8 ± 2.3	11.1 ± 1.5	$p < 0.01$

The correlation coefficients between the variables are shown in Table 10. V_{MART} correlated significantly with V_{max0}, V_{max7}, V_{30m} and peak Bla of the three tests but it did not correlate with VO_{2max0} or VO_{2max7}. VO_{2max7} correlated significantly with V_{max7} but no correlation was observed between VO_{2max0} and V_{max0} or between the running economy and the other variables. Since the triathletes and the cross-country skiers did not differ from each others and formed a homogeneous group with regard to V_{MART} and V_{max0}, the correlation analyses were also done without middle distance runners. However, the correlations were similar.

TABLE 10 Correlations between selected variables measured during the maximal 30-m velocity (V_{30m}) test on a track, the maximal anaerobic running test (MART) on a treadmill and the maximal aerobic power tests at the treadmill inclination of 0° and 7° (subscripts 0 and 7). V_{MART} = maximal velocity in the MART, V_{max} = peak treadmill running velocity, VO_{2max} = maximal oxygen uptake, Bla_{max} and Bla_{MART} = peak blood lactate concentration. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	Bla_{MART}	V_{max0}	VO_{2max0}	Bla_{max0}	V_{max7}	VO_{2max7}	Bla_{max7}	V_{30m}
V_{MART}	0.71 ***	0.85 ***	ns.	0.57 **	0.61 **	ns.	0.46 *	0.96 ***
V_{max0}	ns.	1.00	ns.	0.49 *	0.80 ***	ns.	ns.	0.78 ***
V_{max7}	ns.	0.80 ***	ns.	ns.	1.00	0.78 ***	ns.	0.53 *

5.3 Fatigue-induced changes in metabolic and neuromuscular chracteristics (I, II)

5.3.1 Metabolic characteristics (I)

The track VO_{2peak}, V_{1200m}, VE_{peak} and Bla_{peak} in the 1200-m time trial decreased ($p < 0.05$) after the 10K in both HC and LC but no differences were observed in the pre to post run changes between HC and LC (Table 11). No significant differences or changes were found in VO_2 or VE during the 10K or in peak Bla after the 10K between HC and LC.

TABLE 11 Performance characteristics in the 1200 m time trial (HC = high caliber and LC = low caliber) (means ± SD). Pre= before and post = after 10 km time trial, VO_{2peak} = track maximal oxygen uptake, V_{1200} = mean velocity, VE_{peak} = maximal ventilation, Bla = peak blood lactate concentration after the 1200 m time trial.

	HC pre	HC post	LC pre	LC post	pre vs post
VO_{2peak} ($ml \bullet kg^{-1} \bullet min^{-1}$)	65.9 ± 4.7	65.2 ± 4.7	62.5 ± 3.2	60.1 ± 4.5	p = 0.012
V_{1200} ($m \bullet min^{-1}$)	350.4 ± 8.1	324.3 ± 23.8	332.7 ± 18.0	292.5 ± 15.6	p = 0.000
VE_{peak} ($l \bullet min^{-1}$)	151.9 ± 13.1	145.0 ± 10.7	153.2 ± 12.8	149.4 ± 14.7	p = 0.017
Bla ($mmol \bullet l^{-1}$)	10.5 ± 1.5	9.6 ± 1.7	10.5 ± 2.0	8.6 ± 2.4	p = 0.010

5.3.2 Neuromuscular characteristics (II)

The 10K led to significant changes in all the measured variables of the maximal 20-m runs. V_{20m} decreased ($p < 0.001$) from 7.8 ± 0.4 to 6.1 ± 0.6 m • s^{-1} (22.6 %) in HC and from 7.9 ± 0.4 to 6.1 ± 0.8 m • s^{-1} (23.1 %) in LC. In the maximal 20 m run, the times of the braking, propulsion and the total ground contact phases increased by 26.5 - 37.9 % in both HC and LC after the 10K (Fig. 8). No significant differences were observed between the two groups in the contact times or in the changes of the contact times of the maximal 20 m run.

In both HC and LC, the peak and average vertical and horizontal forces decreased by 5.5 - 17.0 % ($p < 0.05$ - 0.001) after the 10K (Fig. 9A) and the average IEMG of the three measured muscles (VL, BF, GA) during the pre and contact phases were 28.5 - 57.2 % lower ($p < 0.001$) in the $20m_{after}$ than $20m_{before}$ (Fig. 9B). No significant differences were observed in the pre to post run changes between the groups. The IEMG/force ratios of the total contact, braking and propulsion phases decreased by 13.5 - 35.1 % ($p < 0.05$ - 0.001) from the $20m_{before}$ to the $20m_{after}$ in both HC and LC but the changes did not differ between the groups.

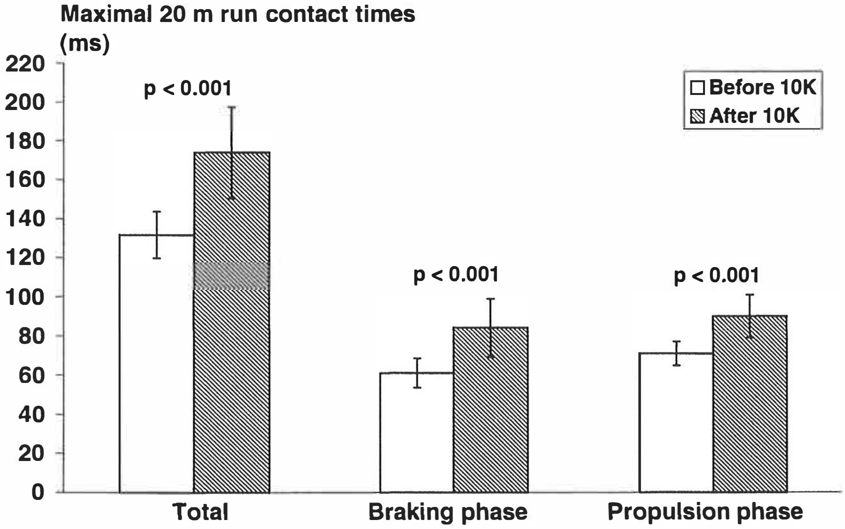
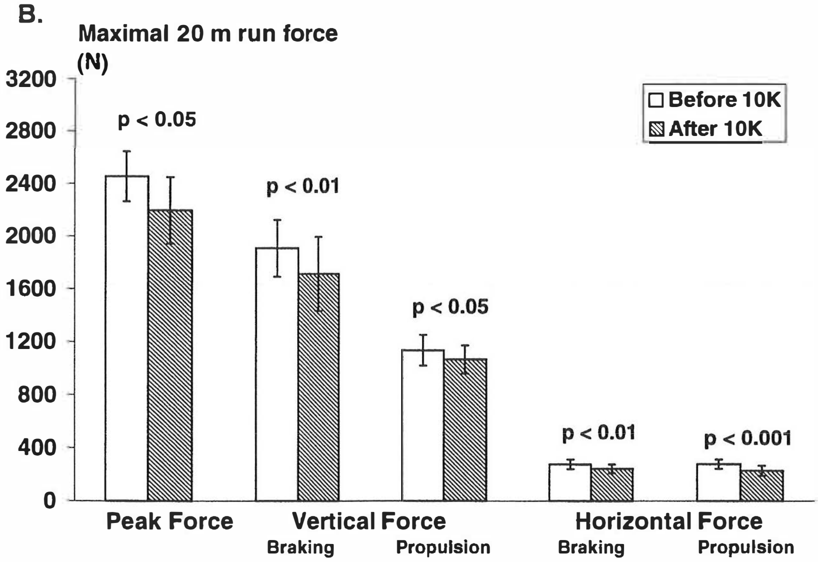


FIGURE 8 The mean total, braking and propulsion phases of the contact times in the maximal 20-m run before and after 10 km time trial (n = 19).



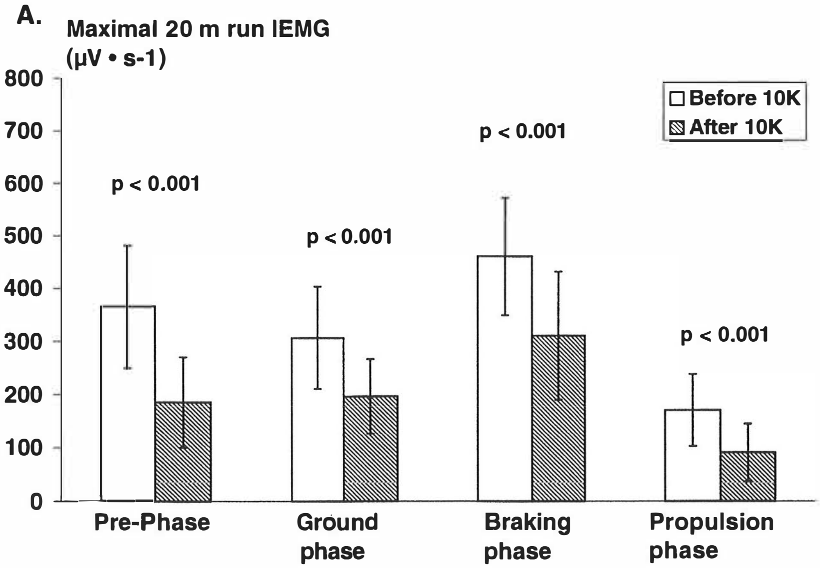


FIGURE 9 The peak and average vertical and horizontal ground reaction forces in the maximal 20 m run before and after 10 km time trial **(A)** and the average integrated electromyographic (IEMG) activity of the three measured muscles (vastus lateralis (VL), biceps femoris (BF) and gastrocnemius (GA)) during the preactivity and ground contact phases in the maximal 20 m run before and after 10 km time trial **(B)** (n = 19).

5.4 Effects of simultaneous explosive-strength and endurance training (V)

The 5K time did not differ significantly between the groups before the experiment but according to analysis of covariance E and C group were different ($p < 0.05$) after training for 5K time. A significant group by training interaction was found in the 5K time after 9 weeks of training. It decreased ($p < 0.05$) during the training period in E group, while no changes were observed in C group (Fig. 10).

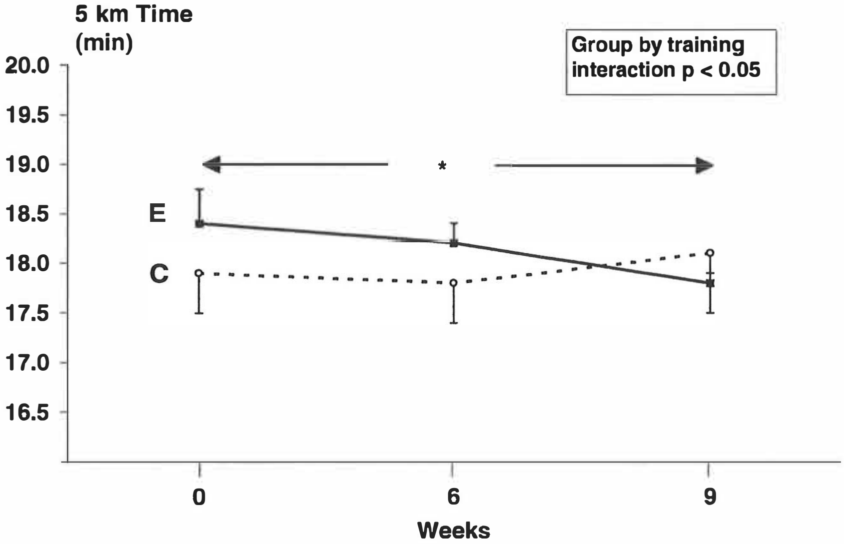


FIGURE 10 The average 5-km running time in the experimental (E) and control (C) groups during the course of 9-week simultaneous explosive-type strength and endurance training. * $p < 0.05$.

The RE, V_{MART} and VO_{2max}demand did not differ between the groups before the experiment but after 9 weeks of training RE ($p < 0.001$) and V_{MART} ($p < 0.01$) of E and C group were different. A significant group by training interaction was found in RE and V_{MART} after the training period and RE, V_{MART} as well as VO_{2max}demand improved ($p < 0.05$) in E group, while no changes were observed in C group (Fig. 11 and 12 and Table 12). Significant group by training interaction ($p < 0.05$) was also found in VO_{2max} after 9 weeks of training with an increase in C group ($p < 0.01$) and no change in E group (Table 12). No significant changes or differences were found either in E or C group in lactate threshold during the training period (Table 12).

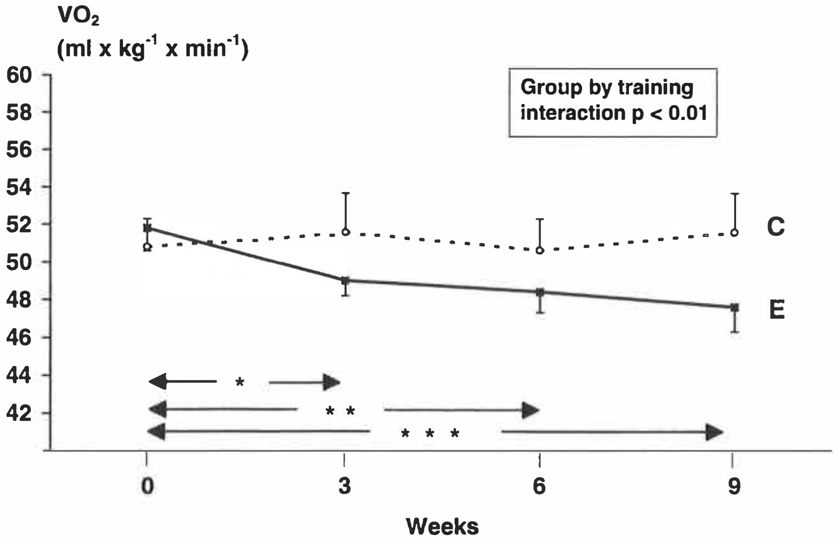


FIGURE 11 The average oxygen uptake of submaximal running economy runs in the experimental (E) and control (C) groups during the course of a 9-week simultaneous explosive type strength and endurance training. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

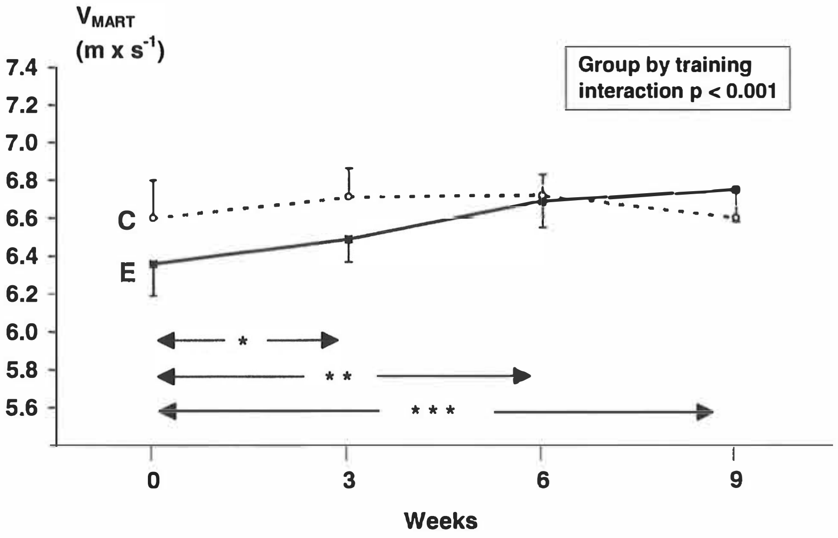


FIGURE 12 The average maximal velocity of the MART (Maximal anaerobic running test) in the experimental (E) and control (C) groups during the course of 9-week simultaneous explosive type strength and endurance training. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

TABLE 12 Peak uphill treadmill running performance (VO_{2max}demand), maximal oxygen uptake (VO_{2max}) and lactate threshold (LacT) of the experimental and control groups in the maximal aerobic power test on the treadmill before and after 3, 6 and 9 weeks of training.

Variable	Experimental group (n = 10)				Control group (n = 8)				
	Before	After 3 wk	After 6 wk	After 9 wk	Before	After 3 wk	After 6 wk	After 9 wk	Interaction
VO_{2max}demand (ml•kg^{-1}•min^{-1})	67.7 ± 2.8	68.4 ± 3.1	68.9 ± 2.8	70.2 ± 2.5[a]	68.3 ± 3.1	68.4 ± 3.6	68.9 ± 2.8	69.2 ± 3.1	ns.
VO_{2max} (ml•kg^{-1}•min^{-1})	63.7 ± 2.7	63.9 ± 1.9	63.4 ± 3.7	62.9 ± 3.2	65.1 ± 4.1	65.3 ± 5.9	67.1 ± 4.1	68.3 ± 3.4[b]	$p < 0.05$.
LacT (ml•kg^{-1}•min^{-1})	47.3 ± 3.3	47.9 ± 2.5	47.8 ± 3.4	48.1 ± 3.5	48.9 ± 4.5	48.9 ± 3.3	49.1 ± 2.1	49.3 ± 2.8	ns.

[a] significantly different from before, $p < 0.05$
[b] significantly different from before, $p < 0.01$

Maximal isometric force of the leg extensor muscles, V_{20m} and 5J did not differ significantly between E and C before the experiment but analysis of covariance showed significant ($p < 0.01$) differences after 9 weeks of training (Table 13). Maximal isometric force tended to increase in E group and to decrease in C group during the training period. The changes were not statistically significant but a significant group by training interaction was found in maximal isometric force (Table 13). V_{20m} and 5J increased in E group by 3.6 to 4.7 % ($p < 0.01$) and decreased in C group by 1.7 to 2.4 % ($p < 0.05$) after 9 weeks of training and significant group by training interactions were observed as well (Table 13). During the CVLs of the 5K, the contact times decreased in E group ($p < 0.001$) and increased in C group ($p < 0.05$) during the training period (Fig. 13). Significant differences ($p < 0.001$) were observed in mean contact times of CVLs between E and C group after training. No significant differences or changes during the training period were observed in either E or C in the ground reaction forces, stride rates or stride lengths of CVLs during the 5K.

The correlation analysis of pooled data showed that the improvement in the 5K velocity correlated significantly ($p < 0.05$) with the improvement in VO_{2max}demand ($r = 0.63$), RE (expressed in VO_2, ml • kg^{-1} • min^{-1}) ($r = - 0.54$) and V_{MART} ($r = 0.55$). The correlation coefficient between the changes in VO_{2max} and in the 5K velocity was negative ($r = - 0.52$, $p < 0.05$). The improvements in RE and V_{MART} correlated with each other ($r = -0.65$, $p < 0.01$) and were associated ($p < 0.05$) with increases in VO_{2max}demand ($r = -0.62$ and 0.64), 5J ($r = -0.63$ and 0.68) and V_{20m} ($r = -0.49$ and 0.69), respectively.

TABLE 13 Maximal isometric strength (F), maximal 20-m run velocity (V_{20m}), 5-jump (5J) and mean contact times of constant velocity laps during 5K (CT_{5K}) of the experimental and control groups before and after 3, 6 and 9 weeks of training.

Variable	Experimental group (n = 10)				Control group (n = 8)				
	Before	After 3 wk	After 6 wk	After 9 wk	Before	After 3 wk	After 6 wk	After 9 wk	Interaction
F (N)	4094 ± 891	4123 ± 913	4226 ± 987	4385 ±1132	3899 ± 635	3712 ± 362	3651 ± 498	3396 ± 648	$p < 0.01$
$V_{20m} (m \bullet s^{-1})$	7.96 ± 0.57	8.05 ± 0.53	8.11 ± 0.51	8.23 ± 0.54[b]	8.28 ± 0.35	8.21 ± 0.38	8.14 ± 0.21[a]	8.08 ± 0.31[a]	$p < 0.001$
5J (m)	12.47 ± 0.90	12.60 ± 0.85	12.86 ± 0.95[b]	13.04 ± 0.83[c]	13.17 ± 0.46	13.08 ± 0.59	13.10 ± 0.47	12.95 ± 0.50[a]	$p < 0.001$
CT_{5K} (ms)	209 ± 14	-	198 ± 16[b]	195 ± 14[c]	196 ± 15	-	199 ± 16	204 ± 17[a]	$p < 0.001$

[a] significantly different from before, $p < 0.05$

[b] significantly different from before, $p < 0.01$

[c] significantly different from before, $p < 0.001$

6 DISCUSSION

6.1 Primary findings

The main findings in the present study were as follows:

1. A strong correlation was observed between VO_{2max}demand and V_{10K} and V_{5K}. The high and low caliber endurance runners differed in their treadmill and track running performance without significant differences in treadmill VO_{2max}, peak Bla, threshold or running economy variables.

2. The present 10K led to a significant reduction in the neuromuscular characteristics (velocity, IEMG, contact times and force production) of the maximal 20-m runs as well as aerobic capacity immediately after 10K. The fatigue-induced changes in the measured metabolic or neuromuscular characteristics did not differentiate between the high and low caliber runners.

3. The high caliber runners reached higher maximal oxygen uptake on the track compared to uphill treadmill running than low caliber runners.

4. A significant correlation was observed between the mean contact times (CT) of constant velocity laps (CVL) and V_{10K} and V_{5K}. V_{5K} correlated also with V_{20m}, CTs and stride rates in the maximal 20-m run and V_{30m} correlated with horizontal (V_{max0}) and uphill (V_{max7}) treadmill running performance.

5. The high caliber endurance runners (HC) had significantly shorter CTs of CVLs during the 10K than the low caliber runners (LC). Preactivity of the gastrocnemius in relation to the IEMG of the total contact phase during the CVLs was higher in HC than LC. The relative IEMGs of the vastus lateralis and gastrocnemius in the propulsion phase compared to the IEMG of the maximal 20m running were lower in HC than LC.

6. During horizontal running V_{max} was significantly higher but VO_{2max}, ventilation and Bla were significantly lower than during uphill running. V_{MART} was related to peak running performance on the horizontal track (V_{5K}) and treadmill (V_{max0}) and uphill treadmill (V_{max7}) running. The middle distance runners had a significantly higher V_{MART} and V_{max0} than the triathletes and cross-country skiers but VO_{2max0} did not differentiate between the athletes groups and no correlation was observed between V_{max0} and VO_{2max0}. Uphill running performance (V_{max7}) correlated significantly with VO_{2max7} and no significant differences were observed in V_{max7} and VO_{2max7} between the groups.

7. V_{MART} correlated significantly with peak blood lactate concentration in MART (peak Bla_{MART}), V_{20m} or V_{30m}, and CT in the maximal 20-m run but not with VO_{2max}. The middle distance runners had a significantly higher V_{MART}, V_{30m} and peak Bla_{MART} than the triathletes and cross-country skiers.

8. Simultaneous explosive strength and endurance training improved the 5-km running performance, neuromuscular characteristics (V_{20m}, 5J and CTs of CVLs), V_{MART}, running economy and peak treadmill running performance but not VO_{2max}.

6.2 Aerobic power, running economy and VO_{2max} demand as determinants of running performance in endurance athletes

It has been well documented that the treadmill VO_{2max} (e.g. Costill et al. 1973, Foster et al. 1978, Foster 1983), lactate and ventilatory thresholds (e.g. Powers et al. 1983, Tanaka et al. 1986, Noakes et al. 1990) as well as running economy (e.g. Conley and Krahenbuhl 1980, Daniels 1985, Morgan et al. 1989b) of endurance athletes are important determinants of distance running performance. The present correlations and stepwise multiple regression analyses showed that, RCT and track running economy were important determinants of 5-km running performance. However, the high and low caliber runners differed in their treadmill and track running performance without significant differences in treadmill VO_{2max}, peak Bla, LacT, RCT or running economy, although these metabolic variables correlated significantly with the velocity of 10K and 5K.

The peak treadmill running performance (VO_{2max}demand) correlated highly significantly with the V_{10K} and V_{5K}. These relationships support the findings of several previous studies (Scrimgeour et al. 1986, Noakes 1988, Morgan et al. 1989a, Noakes et al. 1990, Houmard et al. 1991b, Hill and Rowell 1996, Billat and Koralsztein 1996) that peak running performance (velocity) attained during the treadmill running VO_{2max}test (vVO_{2max}) may be a better indicator of endurance performance in middle- and long-distance running events than VO_{2max} or running economy alone. vVO_{2max} has also been used for the prescription of training for distance runners (Billat and Koralsztein 1996, Billat et al. 1999). Furthermore, time to exhaustion at vVO_{2max} (critical velocity) has been shown to convey valuable information when analysing a runner's performance over the distances from 1500m to the marathon (Billat et al. 1995, Billat and Koralsztein 1996). Daniels (1985) and Morgan et al. (1989a) have determined

vVO_{2max} by extrapolating it from the submaximal velocity and steady-state VO_2 relationship to predict the velocity that would be associated with VO_{2max}. It has been suggested (Daniels 1985, Hill and Rowell 1996) that vVO_{2max} is a parameter which may be described as an integrated product of VO_{2max} and running economy. Some other researchers (e.g. Billat et al. 1994, Billat and Koralztain 1996) have reported vVO_{2max} as the treadmill speed at which an athlete is running when VO_{2max} is elicited or (e.g. Scrimgeour et al. 1986, Noakes et al. 1990, Houmard et al. 1991b) as the final treadmill speed that can be sustained by an athlete, regardless of the actual speed at which VO_{2max} is elicited. Nevertheless, these latter definitions describe vVO_{2max} as a "real" peak velocity (no calculations are involved) in which, in addition to aerobic processes, neuromuscular and anaerobic characteristics are also involved (Noakes 1988, Hill and Rowell 1996).

6.3 Fatigue-induced changes in metabolic and neuromuscular characteristics did not differentiate high and low caliber runners

Neuromuscular fatigue during a large number of repetitive stretch-shortening cycle exercises has been examined in both prolonged (Nicol et al. 1991a, Viitasalo et al. 1982) and short-term intensive exercises (Moritani et al. 1990, Nummela et al. 1994). An acute decrease in force generating capacity during the development of fatigue has been demonstrated, and it seems to be linked to both metabolic (e.g. Linnarsson and Eklund 1982) and neural changes (e.g. Moritani et al. 1990, Nicol et al. 1991a). The present 10K led to a significant reduction in velocity and force production in the maximal 20-m runs after the 10K (Figure 8 and 9). Together with the significant reduction in V_{1200}, VO_{2peak}, VE_{peak} and peak Bla in the 1200-m time trial on the track (Table 11) it indicates that considerable fatigue took place in both high and low caliber runners during the 10K.

Linnarsson and Eklund (1982) have speculated that decreased VO_{2max} after prolonged exercise may be caused by a decreased ability to supply energy anaerobically long enough to allow VO_2 to rise to its potential maximum level. On the other hand, neuromuscular fatigue can be peripheral, relating to a failure of the sarcolemma and sarcoplasmic reticulum in the excitation and contraction processes, but also, in part, of central origin (Green 1987). Previous studies examining repetitive stretch-shortening cycle performances have demonstrated a decreased force generating capacity due to fatigue in short-term intensive exercises (Moritani et al. 1990, Nummela et al. 1994) . It is interesting to notice that the changes in the neuromuscular function were very similar in the present study and in a previous marathon study (Nicol et al. 1991a), although the causes of muscle fatigue were probably different in the distance running compared to jumping or sprint running.

The analysis of the pooled data of the present study showed that both the braking and propulsion phases of the ground contacts were longer after the 10K than before it. This suggests, according to Nicol et al. (1991a), that a time delay between the stretch and the shortening action may have become longer.

Moreover, significant decreases were observed in peak and average vertical forces, especially in the braking phase, associated with the decreased muscle activation in the maximal 20-m runs recorded immediately after the present 10K. These results suggest that a large number of repetitive stretch loads during the 10K decreased the capacity of the neuromuscular system to generate force rapidly and to tolerate impact forces, as also suggested by Gollhofer et al. 1987a, Nicol et al. 1991a and Mero et al. 1992. The possible failure in stiffness characteristics and longer transition time between the braking and propulsion phases reduced the storage of elastic energy during the braking phase, because the ability to store and use of elastic energy is affected by the pre-activity of the muscles (e.g. Dietz et al. 1979), coupling-time, velocity of stretch and muscle stiffness (e.g. Bosco et al. 1981, Enoka 1988b, Komi 1991, Nicol et al. 1991a). The function of the pre-activation is to increase muscle stiffness to tolerate a high impact load (Mero et al. 1992). Therefore, one possible explanation may be a failure of the muscle stiffness in the braking phase (Nummela et al. 1994). The correlation observed between the decreased pre-activity and horizontal ground reaction forces in the braking phase supports this suggestion.

The dramatic decrease in the IEMG - activity of the maximal 20-m runs after the 10K indicates that a large amount of the repeated stretch-shortening cycles during the 10K worsened the force production by reducing neural input to the agonist muscles. This is well in line with fatigue-induced changes reported during prolonged running (Nicol et al. 1991b). It further suggests, together with the decreased IEMG/F ratio, that fatigue under the present experimental conditions might have been not only peripheral but also, in part, of central origin (Bigland-Ritchie et al. 1978, Asmussen 1979, Paavolainen et al. 1994). The latter suggestion is further supported by the finding that the pre-activation, which is preprogrammed from higher centres of the central nervous system (Melvill-Jones and Watt 1971, Moritani et al. 1990) also decreased drastically in the maximal 20-m runs recorded immediately after the 10K.

One of the purposes of the present study was to examine to what extent fatigue-induced changes in the neuromuscular system may determine distance running performance in well trained endurance athletes who are homogeneous with regard to their aerobic capacity. The data showed clearly that considerable fatigue-induced changes in the maximal 20-m run and in the 1200-m time trial were observed in both the high and low caliber runners after the 10K, but no significant differences were found between the groups. The data further demonstrated that no significant changes took place either in VO_2 or VE during the 10K or in the contact times, ground reaction forces or IEMG-activities during the constant velocity laps of the 10K. These results suggest that fatigue related to the cardiovascular and respiratory determinants of maximal oxygen uptake or to anaerobic or neuromuscular characteristics were not the main reasons for the differences in distance running performance between the high and low caliber runners. This observation is well in line with the data by Siler and Martin (1991) reporting that some individuals are more sensitive to the effects of distance running fatigue than the others but there are no significant differences between the fast and slow distance runners in the running pattern with the onset of fatigue. The results further support the observations by Williams et al. (1991)

that fatigue does not necessarily result in marked changes in kinematics during submaximal distance running.

6.4 Neuromuscular characteristics and muscle power as determinants of running performance in endurance athletes

Since aerobic power variables or fatigue-induced changes in metabolic and neuromuscular characteristics did not differentiate the high and low caliber runners, there is a need for further discussion of some other possible determinants of endurance performance. The uphill treadmill VO_{2max} and horizontal track VO_{2peak} correlated with each other, but the treadmill VO_{2max} was significantly higher than the track VO_{2peak}, inspite of the fact that the maximal treadmill test was much longer than the track test. The differences between treadmill VO_{2max} and track VO_{2peak} as well as the differences between treadmill VE_{max} and track VE_{peak} (see Figure 6) were significantly lower in the high caliber runners than in the low caliber runners. Those differences also correlated slightly with V_{10K}, as could be seen in Figure 7. Furthermore, the V_{10K} correlated with the velocity of 1200_{pre} and the high caliber runners had significantly higher track VO_{2peak} and V_{1200m} than the low caliber runners. All these results suggest that maximal oxygen uptake and running performance on a horizontal track may not only be limited by central factors related to oxygen transport and confirm that some other factors, e.g. neuromuscular characteristics and muscle power, cannot be excluded as partial determinants of endurance performance.

6.4.1 Neuromuscular characteristics and running performance

The present data showed clearly that, in addition to aerobic power and running economy, the neuromuscular characteristics were also related to the 5-km and 10-km running performance, although V_{5K} or V_{10K} did not correlate with the ground reaction forces (see Table 7, Figure 5). The V_{5K} correlated with V_{20m}, CTs and SRs of the maximal 20-m run. Both V_{5K} and V_{10K} also correlated with the mean CT of the constant velocity laps during the 5K and 10K. These results and the differences observed in the mean ground contact times of the constant velocity laps during the 10K between the high and low caliber runners suggest that the ability for fast force production during maximal and submaximal running was related to the 5-km and 10-km running performance.

There are several explanations for the differences in ground contact times between the athletes. Differences in velocity affect contact times and stride rates (Luhtanen and Komi 1978). However, factors other than velocity must have influenced the biomechanical parameters measured during the constant velocity laps in the present study. High stride rates and short ground contact times, especially in the braking phase have been found to influence sprint running performance (e.g. Mann and Herman 1985, Mero et al. 1992). Williams (1985) has found that also during submaximal running ground contact times differ between a rearfoot and a midfoot striker. Some other kinematic or anthropometric factors (e.g. Williams 1985) might also explain the differences in contact times between athletes. Although the present endurance athletes were relatively homogeneous with regard to physiological and running performance characteristics, their muscle fiber compositions might have been different and could explain the differences in their neuromuscular characteristics (e.g. Goldspink 1991). Viitasalo and Komi (1978) have shown that force-time characteristics differ between subjects with different compositions of fast- and slow-twitch fibers in their muscles. Force output of muscle contraction is also known to depend on the rate and force of myofibrillar cross-bridge cycle activity and effective storage and release of elastic energy during stretch-shortening cycle exercises (e.g. Bosco et al. 1981, Enoka 1988a).

Elasticity in muscles and tendons plays an important role in enhancing both the effectiveness and the efficiency of human performance. The ability of muscles to store and utilize elastic energy depends on stretching velocity and muscle length in the prestretch action. High pre-activation plays a major role by increasing muscle stiffness and leading to a faster transition from the braking to the propulsion phase (e.g. Bosco et al. 1981, Dietz et al. 1979, Enoka 1988b, Komi 1984). After the short braking phase the recoil of elastic energy during the propulsion phase increases and the improved efficiency could in part come from elastic energy so that lowered muscular activation becomes possible during the propulsion phase (Williams 1985). Neither the coupling-times nor muscle stiffness were measured in the present study. However, the high caliber runners had shorter contact times in the braking phases, higher relative pre-activation and lower relative agonist IEMG-activity during the propulsion phases in the constant velocity laps of the 10K than the low caliber runners (Figure 5). These data indicate that voluntary and/or reflex neural control in the stretch-shortening cycle performance with the capability to store and utilize the elastic energy may play important roles throughout the 10K performance.

The importance of neuromuscular characteristics as determinants of running performance was also supported by the findings that peak horizontal (V_{max0}) and uphill (V_{max7}) treadmill running performance correlated with V_{30m} (Table 10). Furthermore, during horizontal running the athletes attained significantly higher V_{max0}, but the maximal values for VO_2, ventilation and blood lactate concentration were all significantly lower than values measured at exhaustion during uphill running. Pokan et al. (1995) have also shown that VO_{2max} is lower during horizontal than uphill treadmill running. As could be expected, the middle distance runners had significantly higher V_{max0} and V_{30m} than the other two groups, but VO_{2max0} did not differ between the athlete groups. All these results confirm that the neuromuscular characteristics of muscles are important for maximal uphill and, especially, for horizontal running performance and that the central factors related to oxygen transport are not the only determinants of V_{max0} , as also suggested by Pokan et al. (1995).

6.4.2 Muscle power and running performance

So far the discussion has focused on the possibility that neuromuscular characteristics may have an important role as determinants of running performance. Bulbulian et al. (1986) and Houmard et al. (1991a) have shown that anaerobic characteristics can also differentiate between well trained endurance athletes according to their distance running performance. In the present study, the middle distance runners had significantly higher Bla during horizontal and uphill running than the triathletes and cross-country skiers and Bla_{max0} correlated with V_{max0}. These findings confirm that, in addition to neuromuscular characteristics, anaerobic power and capacity may also be important for distance running performance in well trained endurance athletes.

Noakes (1988) has suggested that maximal exercise performance and VO_{2max} may not be limited only by central factors related to oxygen uptake, but also by the so called muscle power factors, which seem to be related to neuromuscular and anaerobic characteristics (Noakes 1988, Green and Patla 1992, Liefeldt et al. 1992, Rusko et al. 1993, Rusko and Nummela 1996). However, muscle power has not been defined and relatively few studies have investigated the importance of muscle power as the determinant of endurance performance. Based on the reviews by Noakes (1988) and Green and Patla (1992), muscle power was defined in this study as the ability of the neuromuscular system to produce power during maximal exercise when glycolytic and/or oxidative energy production is high and muscle contractility may be limited. In this definition, muscle power is not a physical term but refers to the original theoretical concept of Noakes (1988). Previous studies have shown that an increased H+ ion concentration, which is related to the increased blood lactate concentration, may impair the contractile properties of the muscles (e.g. Mainwood and Renaud 1985, Green and Patla 1992). During middle distance running and uphill cross country skiing, energy expenditure may exceed maximal aerobic power and the athletes must be able to maintain a relatively high velocity over the course of a race, although their muscle and blood lactate concentrations are high (Di Prampero et al. 1993, Norman et al. 1989). This further emphasizes the importance of muscle power in endurance sport (Rusko and Nummela 1996).

One problem in the present study was to analyze the importance of muscle power (V_{MART}) as well as central factors (VO_{2max}) as determinants of peak horizontal and uphill running performance. The stepwise multiple regression analysis showed that not only running economy and the respiratory compensation threshold but also V_{MART} was important for 5-km running performance (see Table 7). Furthermore, although the middle distance runners had a significantly higher V_{max0} and V_{MART} than the other two groups, VO_{2max0} did not differentiate between the athlete groups and no correlation was observed between V_{max0} and VO_{2max0}. Instead of that, V_{MART} correlated highly significantly with V_{max0} and also with V_{5K}. It should also be taken into account that during the MART, 5K and treadmill running the athletes had to use their neuromuscular characteristics when oxygen uptake and blood lactate concentrations were considerably increased over rest values. Therefore, the neuromuscular system must be capable to produce repeatedly high contraction velocities during all these exercise tests. All these results suggest that not only neuromuscular and anaerobic characteristics separately but also muscle power was important for high horizontal running performance and that the central factors related to oxygen transport were not the only determinants of peak track and treadmill running performance. This is well in line with Noakes (1988) who has also suggested that maximal exercise performance may not always terminate when there is a limiting rate of oxygen transport but could be determined by muscle power factors, in particular those controlling the rate and force of myofibrillar cross-bridge cycle activity.

Peak uphill treadmill running performance (V_{max7}) also correlated significantly with V_{MART} and V_{30m}, suggesting that muscle power and related neuromuscular and anaerobic characteristics are also important for maximal uphill running performance. However, V_{max7} also correlated significantly with VO_{2max7} and VO_{2max7} was significantly higher than VO_{2max0}, suggesting that central cardiovascular and respiratory factors related to oxygen uptake, are more important during uphill than horizontal running. The increased importance of VO_{2max} during uphill running could reflect the involvement of an increased muscle mass (Olesen 1992, Sloniger et al. 1997a) and different muscle fibres (Costill et al. 1974). Sloniger et al. (1997b) have also found that greater total muscle activation during exhaustive uphill than horizontal running is achieved through an altered pattern of muscle activation that involves increased use of lower extremity muscles. Altered efficiency with an increasing gradient treadmill could also increase energy expenditure during uphill running (Margaria et al. 1963, Olesen 1992, Pokan et al. 1995, Sloniger et al. 1997a), although Kaneko et al. (1985) have suggested that a reduction in velocity may increase efficiency at high uphill running gradients.

Examples based on individual data from the present study illustrate the increasing importance of muscle power as well as neuromuscular characteristics for distance running performance in homogeneous endurance athletes who already have attained a high level of aerobic capacity (Appendix 1-3). There were no differences in VO_{2max} or RCT between subjects A and B, but subject B had better running economy, V_{MART} and V_{20m} and shorter contact times, which seemed to be consistent with his faster 5-km running time. On the other hand, another example shows that individual performance may be associated with a different combination of aerobic power and economy variables as well as neuromuscular and anaerobic ability. Subject C achieved his 5-km running time with a combination of higher VO_{2max} and RCT than subject D, while subject D had relatively low aerobic capacity but better running economy and neuromuscular characteristics compared to subject C.

6.4.3 V_{MART} as a measure of muscle power

Although it has been suggested that maximal exercise performance may be limited by muscle power, there are no generally accepted methods or tests to measure or evaluate muscle power. Noakes (1988) has suggested that the peak velocity sustained for 1 min at the end of an incremental treadmill running test to exhaustion could be used as a measure of the muscle power of distance runners. The present correlation observed between V_{5K} and VO_{2max}demand indicates that peak treadmill running performance is a good predictor of track running performance, which is in agreement with some previous studies (e.g. Houmard et al. 1991b, Noakes et al. 1990). As expected, the results of the correlation and regression analyses showed that aerobic power and economy parameters predominated as determinants of VO_{2max}demand. This supports the previous suggestions (e.g. Hill and Rowell 1996) that although neuromuscular and anaerobic characteristics may be involved in peak treadmill running performance, the role of aerobic processes is also important.

Rusko et al. (1993) have developed the V_{MART} test to measure both neuromuscular and anaerobic determinants of maximal anaerobic running performance. It has been shown that V_{MART} is influenced by both the anaerobic power and capacity and neuromuscular characteristics but not by aerobic power factors (e.g. VO_{2max}) and that it can also be used as a measure of muscle power in sprinters (Rusko et al. 1993, Rusko and Nummela 1996). Furthermore, V_{MART} has also been shown to correlate with accumulated oxygen deficit (Maxwell and Nimmo 1994). In the present study, V_{MART} correlated significantly not only with neuromuscular and anaerobic characteristics (ground contact times in the maximal 20-m run, V_{20m}, V_{30m} and peak Bla_{MART}) but also with 5-km running performance, suggesting that V_{MART} could be used as a measure of muscle power of distance runners. These findings are supported by the results that V_{MART} correlated highly significantly with peak blood lactate concentration in horizontal (Bla_{max0}) and uphill (Bla_{max7}) running but not with VO_{2max}. Furthermore, the middle distance runners had the highest V_{MART} that was related to better V_{30m} and peak Bla_{MART} as compared to the triathletes and cross country skiers. In consequence, all these data suggest that interaction of neuromuscular and anaerobic characteristics influence V_{MART}. In contrast to peak treadmill running velocity or VO_{2max}demand, V_{MART} was not related to VO_{2max} or the other aerobic power variables. Therefore V_{MART} is suggested to be a better measure of muscle power in endurance athletes than peak treadmill running performance, although the biomechanical, neuromuscular and anaerobic characteristics influencing V_{MART} are not yet fully understood.

6.5 Effects of simultaneous explosive strength and endurance training

The present 9-week explosive type strength training resulted in considerable improvements in selected neuromuscular characteristics, although a large volume of the endurance training was performed concomitantly. This was demonstrated by the significant improvements in V_{20m}, 5J, and by the shortening of the contact times during the constant velocity laps of the 5K, while no changes were observed in the ground reaction forces or maximal force of the trained muscles. These results support previous findings (Paavolainen et al. 1991) that in well trained endurance athletes training-induced improvements in neuromuscular characteristics may not be fully inhibited by training simultaneously explosive strength and endurance.

Aura and Komi (1986) and Kyröläinen et al. (1991) have suggested that the nervous system plays an important role in regulating muscle stiffness and utilization of muscle elasticity during stretch-shortening cycle exercises in which high contraction velocities are used. The present increases in the neuromuscular performance characteristics might primarily be due to neural adaptations, although no electromyographic measurements on the muscles were done to support this suggestion. Although the loads used in the present explosive strength training were low, the muscles are known to be highly activated due to the maximal movement velocity utilized (Häkkinen 1994). It has been shown that this type of explosive strength training results in increases in the amount of neural input to the muscles observable during rapid dynamic and isometric actions (e.g. Häkkinen et al. 1985, Häkkinen and Komi 1985) suggesting that the increase in net excitation of motoneurones could result from increased excitatory input, reduced inhibitory input or both (Sale 1991). It is likely that training-induced alterations in neural control during stretch-shortening cycle exercises such as running and jumping may take place in both voluntary activation and inhibitory and/or facilitatory reflexes (Häkkinen and Komi 1985, Kyröläinen et al. 1989, Sale 1991, Häkkinen 1994). Although neural activation of the trained muscles during explosive type strength training is very high, the time of this activation during each single muscle action is usually so short that training-induced muscular hypertrophy and maximal strength development takes place to a drastically smaller degree than during typical heavy resistance training (Häkkinen 1994). Consequently, it has been suggested (Paavolainen et al. 1991) that during relatively short training periods of some weeks the improvements in sprinting and/or explosive force production capacity, especially in endurance athletes, might primarily come from neural adaptations without observable muscle hypertrophy (see also Hickson et al. 1980, Hickson et al. 1988). The finding that no changes took place in the circumferences of the calf and thigh muscles of the present endurance athletes during the training period supports this suggestion.

It has been shown (Rusko 1992) that adult endurance athletes who continue their endurance training for several years seem to reach a more or less apparent ceiling of VO_{2max} and endurance performance. The rationale for the present training study was based on the hypothesis that endurance performance is influenced not only by aerobic power and running economy but also by the muscle power related to neuromuscular and anaerobic characteristics. This hypothesis was supported by the finding that the improvements in the 5-km running performance of the experimental athletes took place without changes in their VO_{2max} or LacT. Interestingly, even a negative correlation was observed between the individual changes in VO_{2max} and the changes in the 5K velocity. Furthermore, the control group showed increased VO_{2max} but did not demonstrate changes in the 5-km running performance. An interesting finding which further supports the hypothesis of muscle power was that although the improvements in the neuromuscular characteristics (V_{20m}, 5J, CTs of CVLs) during the training period did not correlate directly with the changes of 5-km running performance, they correlated with the improvement in V_{MART}. Moreover, the changes in V_{MART} were associated with improved V_{5K}. These results further support the observation by Nummela et al. (1996c) that training which utilizes various jumping and sprinting exercises with high contraction velocities and reaction forces results in increases in stretch-shortening cycle exercises such as sprint running, also allowing improvements in V_{MART}. Furthermore, these results are in line with our previous observation that V_{MART} is influenced by the interaction of neuromuscular and anaerobic characteristics and that V_{MART} can be used as a measure of muscle power.

Another possible mechanism for the improvement in the 5-km running performance during the training period seemed to be related to running economy. It has been reported (Johnston et al. 1997) that heavy resistance strength training improved the running economy of female distance runners. The importance of neuromuscular characteristics in determining running economy and thereby running performance has also recently been pointed out by Heise et al. (1996) and by Dalleau et al. (1998). According to Heise et al. (1996), more economical runners may use increased joint stiffness to their advantage so that during contact phase, runners may require less metabolic energy. Dalleau et al. (1998) showed that the energy cost of running is significantly related to the stiffness of the propulsive leg, which is also demonstrated by the present decrease in the CTs of CVLs and increase of V_{20m} and 5J in E group. It has been suggested (Di Prampero et al. 1993) that the 5 % decrease in the energy cost of running explains an improvement of distance running performance time of about 3.8 %. This is in line with the results of the present study in which running economy and 5K time of experimental group improved by 8.1 % and 3.1 %, respectively, and no changes in VO_{2max} were observed. Furthermore, the present correlations between the improvements in the neuromuscular characteristics and running economy were statistically significant. All these findings together with the relationship between the improvement in V_{5K} and running economy suggest that explosive strength training had a positive influence on running economy and running performance due to the improved neuromuscular characteristics. However, running economy at race pace is different from that at submaximal running velocity. The significant correlation between RE and V_{MART} suggests that muscle power may influence running economy at both submaximal velocities and, most probably, at race pace.

6.6 Hypothetical model of determinants related to distance running performance

It has been well documented that endurance training improves performance, VO_{2max}, submaximal endurance and running economy by improving the cardiorespiratory system and the oxidative capacity and glycogen stores of the muscles (e.g. Rusko et al. 1978, Holloszy and Coyle 1984, Åstrand and Rohdahl 1986). Anaerobic-type endurance training and/or intensive interval training improves anaerobic power and capacity by increasing glycolytic enzymes and buffer capacity (e.g. Roberts et al. 1982, Sharp et al. 1986, Medbø and Burgers 1990). Heavy resistance strength training results in neural and muscle hypertrohic adaptations (e.g. Moritani and DeVries 1979, Häkkinen et al. 1985, Häkkinen 1994). Explosive type strength training leads to specific neural adaptations with the increased rate of activation of the motor units, while muscle hypertrophy takes place to a drastically smaller degree than during heavy resistance training. (e.g. Enoka 1988a, Sale 1991, Häkkinen 1994, see also Figure 3). Some previous training studies (Hickson et al. 1980, Marcinik et al. 1991, McCarthy et al. 1995) have found that strength training may lead to improved endurance performance in previously untrained subjects. The present study showed that simultaneous sport specific explosive strength and endurance training may also improve the 5-km running performance of well trained male endurance athletes. The mechanism of this improvement is suggested to be related to an explosive strength training effect: neuromuscular characteristics measured by V_{20m}, 5J and CTs of CVLs were improved and transferred into improved muscle power (V_{MART}) and running economy. Therefore, Figure 18 presents a hypothetical model describing the determinants of distance running performance. The model takes into account not only endurance training, aerobic power variables and running economy but also proper strength training, neuromuscular characteristics and muscle power.

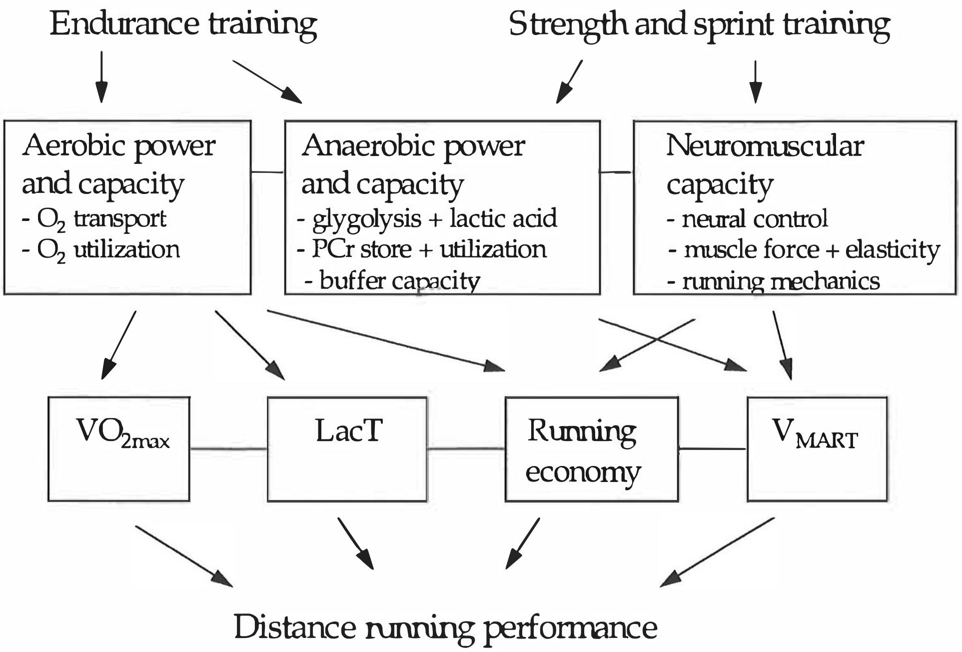


FIGURE 18 A hypothetical model of the determinants of distance running performance explaining the effects and mechanisms of endurance and strength training. PCr = phosphocreatine, VO_{2max} = maximal oxygen uptake, LacT = lactate threshold, V_{MART} = peak velocity in MART.

7 CONCLUSIONS

The conclusions of the present study can be summarized as follows:

1. Peak treadmill running performance (VO_{2max}demand) correlated highly significantly with V_{5K} and V_{10K}. The high and low caliber endurance runners differed in their treadmill and track running performance without significant differences in treadmill VO_{2max}, peak Bla, threshold or running economy variables, although VO_{2max}, LacT and RCT correlated significantly with the velocity of the 10K. These results indicate that peak running performance attained during the treadmill running VO_{2max} test is a better predictor of distance running performance in homogeneous well trained endurance athletes than aerobic power or running economy variables alone because it integrates the influence of VO_{2max}, running economy and neuromuscular and anaerobic characteristics.

2. Although considerable fatigue-induced changes in the maximal 20-m run and in the 1200-m time trial were observed in both the high and low caliber runners after the 10K, the changes were not different between the groups. These results suggest that fatigue related to cardiovascular and respiratory determinants of maximal oxygen uptake or to anaerobic components or neuromuscular characteristics were not the main reasons for the differences in distance running performance between the high and low caliber runners.

3. The high caliber runners reached a higher proportion of the VO_{2max} on a track compared to uphill treadmill running than the low caliber runners. This result together with correlation analysis suggests that maximal oxygen uptake and running performance on a horizontal track or treadmill may not be limited only by central cardiovascular and respiratory factors related to oxygen transport and utilization.

4. The capability of the neuromuscular system to produce force rapidly during the constant velocity laps throughout the 10K and 5K was related to distance running performance. Higher relative pre-activation and lower relative IEMG-activities during the propulsion phase were observed in the high caliber runners compared to low caliber runners. This further suggests that neural control of muscle force production and/or the capability to store and utilize elastic energy may have important roles in determining distance running performance in well trained endurance athletes who do not differ from each other in aerobic capacity.

5. V_{max0}, V_{max7}, VO_{2max}demand and V_{5K} correlated significantly with V_{MART} and V_{20m} or V_{30m} and V_{max7} with VO_{2max7}. In addition VO_{2max7} was significantly higher than VO_{2max0}. These findings indicated that neuromuscular characteristics and muscle power were important for maximal uphill running and especially important for horizontal running performance. They also confirmed that the central cardiovascular and respiratory factors are more important for uphill than horizontal running.

6. V_{MART} correlated significantly with peak Bla_{MART}, V_{20m} or V_{30m}, and CT in the maximal 20-m run but not with VO_{2max}. The middle distance runners had a significantly higher V_{MART}, V_{30m} and peak Bla_{MART} than the triathletes and cross-country skiers. These results suggest that V_{MART} is determined by an interaction of neuromuscular and anaerobic characteristics and that V_{MART} can be used as a measure of muscle power in endurance athletes.

7. Simultaneous explosive strength training and endurance training produced a significant improvement in the 5 km running performance in well trained endurance athletes without changes in VO_{2max} or other aerobic power variables. This improvement was due to improved neuromuscular characteristics which were transferred into improved muscle power and running economy.

8. To summarize, a factor model for distance running performance was constructed using the major determinants of distance running performance in the present study: muscle power, running economy and aerobic power variables (Figure 18). Depending on the duration and "nature" of performance these different factors may have a modifying influence on performance.

8 YHTEENVETO

Tämän vuosisadan alkupuolelta lähtien kestävyyssuorituskyvyn mittaamiseksi on kehitetty lukuisia erilaisia testausmenetelmiä. Tähän asti painopiste kestävyysurheilussa on ollut aineenvaihdunnallisten kunto-ominaisuuksien ja hengitys- ja verenkiertoelimistön kapasiteetin (maksimaalinen hapenottokyky, laktaatti- ja hengityskynnys) testaamisessa. Kestävyysurheilussa vauhdin ja kilpailuvaatimusten systemaattinen kasvu ovat kuitenkin asettaneet uusia vaatimuksia työtä tekevien lihasten ja muun elimistön kyvylle tehdä tehokasta, taloudellista ja nopearytmistä lihastyötä.

Kilpailusuoritukseen olennaisena osana vaikuttavan hermo-lihasjärjestelmän ominaisuuksia ja niiden merkitystä suorituskykyä rajoittavina tekijöinä on kestävyyslajeissa tutkittu vähän. Epäselvää on myös, mitkä kaikki tekijät selittävät kestävyysurheilijan kilpailu- ja suorituskykyisyyttä, miten sitä pystytään mittaamaan ja miten hermo-lihasjärjestelmän toimintaa parantava voimanopeustyyppinen harjoittelu vaikuttaa suorituskykyyn. Noakes (1988) on perusteelliseen kirjallisuuden arviointiin ja tutkimustuloksiin nojautuen esittänyt, että kestävyyssuoritusta rajoittavat sekä fysiologiset hapen kuljetukseen ja käyttöön liittyvät tekijät että hermo-lihasjärjestelmän voimantuottoon ja anaerobiseen tehoon ja kapasiteettiin ("muscle power") liittyvät tekijät. Rusko ja Nummela (1996) ovat kehittäneet suorituskykytestin juoksumatolle (MART, Maximal anaerobic running test), jonka avulla voidaan arvioida hermo-lihasjärjestelmän suorituskykyisyyttä varsinkin pikajuoksijoilla. Tämän tutkimuksen tarkoituksena oli selvittää hermolihas-järjestelmän voimantuotto-ominaisuuksien merkitystä kestävyyssuoritusta rajoittavina tekijöinä ja MART:n soveltuvuutta mitata hermolihasjärjestelmän toimintakapasiteettia kestävyysurheilijoilla. Edelleen tarkoituksena oli selvittää neuromuskulaarisia ominaisuuksia parantavan voimanopeusharjoittelun vaikutuksia kestävyyssuorituskykyyn ja taloudellisuuteen.

Tutkimus koostuu viidestä osatutkimuksesta, joissa mieskestävyysurheilijoita oli tutkittavina yhteensä 65 (42 suunnistajaa, 7 keskimatkojen juoksijaa, 8 triatlonistia ja 8 hiihtäjää). Kestävyyssuorituskykyä mitattiin 5 ja 10 km:n juoksuilla sisähalliradalla. Maksimaalinen hapenottokyky, maksimi työmäärä/ nopeus ja laktaatti- ja hengityskynnys mitattiin aerobisella suoralla maksimitestillä juoksumatolla. Juoksun taloudellisuutta arvioitiin mittaamalla hapenkulutusta submaksimaalisessa juoksutestissä sekä juoksumatolla että sisähalliradalla. Erilaisten hermo-lihasjärjestelmän voima-nopeusmuuttujien, muscle power:n ja väsymyksen merkitystä kestävyyssuorituskykyä selittävinä tekijöinä selvitettiin voimamittauksilla ja mittaamalla lihasten sähköistä aktiivisuutta (EMG), maksimaalisilla 20:n ja 30:n metrin juoksuvedoilla ja suorituskykytestillä (MART). Lisäksi selvitettiin muscle power:n ja maksimaalisen hapenottokyvyn merkitystä tasaisella ja ylämäkijuoksussa. Yhdistetyn nopeusvoima- ja kestävyysharjoittelun vaikutuksia kestävyyssuorituskykyyn, hermo-lihasjärjestelmän voimantuotto-ominaisuuksiin ja juoksun taloudellisuuteen selvitettiin 9 viikon harjoittelujaksolla.

Maksimityömäärä aerobisessa suorassa juoksumattotestissä korreloi vahvasti 5 ja 10 km:n juoksunopeuteen. 10 km:n juoksunopeudeltaan hyvät juoksijat saavuttivat myös tilastollisesti paremman maksimityömäärän juoksumatolla verrattuna heikompitasoisiin juoksijoihin. Hyvät ja huonot juoksijat eivät eronneet maksimaalisessa hapenottokyvyssä tai laktaatti- ja hengityskynnyksissä huolimatta siitä, että nämä kestävyysominaisuudet korreloivat 10 km:n nopeuden kanssa. Nämä tulokset vahvistavat aiempia havaintoja, että homogeenisilla hyvin harjoitelleilla kestävyysurheilijoilla maksimityömäärä/nopeus juoksumatolla selittää kestävyyssuorituskykyä paremmin kuin maksimihapenottokyky, kynnysominaisuudet tai taloudellisuus erikseen.

Urheilijat juoksivat maksimaalisen 20 m:n juoksuvedon sekä 1200 m:n hapenottotestin ennen 10 km:n juoksua ja välittömästi sen jälkeen. 10 km:n juoksu aiheutti tilastollisesti merkitsevät muutokset kaikkiin mitattuihin muuttujiin. Maksimaalinen 20 m:n juoksunopeus, kokonais- ja työntö- ja jarrutusvaiheen kontaktiajat laskivat tilastollisesti merkitsevästi. Selvä tilastollisesti merkitsevä lasku havaittiin myös maksimivoimassa, keskimääräisissä vertikaali- ja horisontaalivoimissa jarrutus- ja työntövaiheissa sekä keskimääräisissä EMG-aktiivisuudessa. Hyvien ja huonojen juoksijoiden välillä ei muutoksissa ollut eroja. Mitattaessa aikaa, hapenottokykyä, ventilaatiota ja veren laktaattipitoisuuksia 1200 m:n juoksuissa, havaittiin, että ne laskivat tilastollisesti merkitsevästi 10 km:n juoksun jälkeen. Hyvien ja huonojen juoksijoiden välillä ei muutoksissa ollut eroja. Nämä tulokset osoittavat, että hermo-lihasjärjestelmän voimantuotto-ominaisuuksien tai fysiologisten hapen kuljetukseen ja käyttöön liittyvien muuttujien väsymisessä ei ollut eroja hyvien ja huonojen juoksijoiden välillä eikä väsyminen näin ollen selittänyt eroja juoksusuorituskyvyssä.

Urheilijat juoksivat sekä 5 että 10 km:n aikana vakionopeuksisia 200 m:n kierroksia, jotta voima- ja EMG-tuloksia voitiin vertailla eri tutkittavien välillä. Tulokset osoittivat, että keskimääräiset kontaktiajat vakionopeuksisilla kierroksilla korreloivat sekä 5 että 10 km:n juoksunopeuteen. 5 km:n juoksunopeus oli myös yhteydessä maksimaaliseen 20 m:n juoksunopeuteen, kontaktiaikoihin ja askeltiheyksiin. Nämä tulokset viittaavat siihen, että hermo-lihasjärjestelmän kyky tuottaa voimaa nopeasti oli yhteydessä kestävyyssuorituskykyyn. Vertailtaessa hyviä ja huonoja juoksijoita havaittiin, että hyvillä keskimääräiset kontaktiajat vakionopeuksisilla kierroksilla olivat lyhyemmät kuin huonoilla. Edelleen havaittiin, että lihasten esiaktiivisuus suhteessa koko kontaktin EMG-aktiivisuuteen vakionopeuksisilla kierroksilla oli hyvillä suurempi kuin huonoilla juoksijoilla. Toisaalta työntövaiheen EMG-aktiivisuus vakionopeuksilla kierroksilla oli maksimaaliseen 20 m:n juoksun EMG-aktiivisuuteen verrattuna hyvillä juoksijoilla pienempi kuin huonoilla. Näiden tulosten perusteella voidaan arvioida, että hyvin harjoitelleilla kestävyysurheilijoilla lihasten voimantuoton neuraalisella kontrollilla ja / tai kyvyllä hyödyntää elastista energiaa kontaktivaiheessa on tärkeä rooli suorituskykyä selittävinä tekijöinä.

Vertailtaessa eri muuttujia tasaisella ja ylämäkijuoksussa havaittiin, että tasaisella maksimijuoksunopeus oli selvästi suurempi kuin ylämäkijuoksussa, vaikka maksimaalinen hapenottokyky, veren laktaattipitoisuus ja ventilaatio olivat ylämäessä suuremmat. MART:n maksiminopeus oli yhteydessä sekä tasaisella että ylämäessä juoksun suorituskykyyn. Edelleen havaittiin, että keskimatkan juoksijat saavuttivat selvästi korkeamman maksiminopeuden sekä MART:ssa että tasaisella juoksussa verrattuna triatlonisteihin ja hiihtäjiin, mutta maksimaalisessa hapenottokyvyssä ei ryhmien välillä ollut eroja, eikä hapenottokyky korreloinut tasaisella juoksun suorituskykyyn. Sitä vastoin maksimaalinen hapenottokyky korreloi selvästi ylämäkijuoksun suorituskykyyn ja ryhmien välillä ei ollut eroja ylämäkijuoksun nopeudessa tai hapenotossa. Nämä tulokset vahvistavat käsitystä, että hermo-lihasjärjestelmän voimantuotto-ominaisuudet ja muscle power ovat tärkeitä varsinkin tasaisella juoksun suorituskyvyn kannalta, kun taas hapen kuljetukseen ja käyttöön liittyvien tekijöiden merkitys kasvaa ylämäkijuoksussa.

Tutkimuksen yhtenä tarkoituksena oli myös selvittää, voidaanko anaerobista suorituskykytestiä (MART) käyttää arvioitaessa kestävyysurheilijan hermolihasjärjestelmän suorituskykyisyyttä. MART:n maksiminopeus korreloi sekä maksimilaktaatin että voima-nopeusmuuttujien kanssa, mutta ei maksimaalisen hapenottokyvyn kanssa. Keskimatkan juoksijoilla oli selvästi suurempi nopeus ja maksimilaktaattipitoisuus MART:ssa ja suurempi 30 m:n juoksunopeus kuin triatlonisteilla ja hiihtäjillä. Nämä tulokset tukevat aiempia havaintoja, jotka ovat osoittaneet, että maksiminopeus MART:ssa koostuu sekä anaerobisesta tehosta ja kapsiteetista että neuromuskulaarisista tekijöistä. Tämän tutkimuksen tulokset edelleen osoittavat, että MART:a voidaan käyttää arvioitaessa kestävyysurheilijoiden hermo-lihasjärjestelmän suorituskykyisyyttä.

Yhdistetyssä nopeusvoima- ja kestävyysharjoittelututkimuksessa mittaukset tehtiin ennen harjoittelujaksoa ja 3, 6 ja 9 viikon harjoittelun jälkeen. Kokonaisharjoittelumäärä oli koe- ja kontrolliryhmällä sama, mutta koeryhmän harjoittelusta 32 % oli lajinomaista nopeus- ja nopeusvoimaharjoittelua (juoksuvetoja, hyppyjä, loikkia ym.). Ryhmien välillä ei lähtötasoissa havaittu tilastollisesti merkitseviä eroja. Harjoitusjakson aikana koeryhmä paransi 5 km:n juoksuaikaa, juoksun taloudellisuutta, MART:n maksiminopeutta, maksimaalisen 20 m:n juoksunopeutta ja 5-loikka tulosta, kun taas kontrolliryhmällä ominaisuudet säilyivät ennallaan tai hieman heikkenivät. Maksimaalinen hapenottokyky ei muuttunut harjoittelujakson aikana koeryhmällä, mutta kontrolliryhmällä se parani tilastollisesti merkitsevästi. Korrelaatioanalyysi osoitti, että 5 km:n ajan paraneminen oli yhteydessä juoksun taloudellisuuden ja MART:n maksiminopeuden paranemiseen. Tulokset osoittivat, että hyvin harjoitelleilla kestävyysurheilijoilla yhdistetty nopeusvoima- ja kestävyysharjoittelu parantaa kestävyyssuorituskykyä ilman, että maksimaalinen hapenottokyky heikkenee. Parannukset suorituskyvyssä johtuivat hermo-lihasjärjestelmän voimantuotto-ominaisuuksien paranemisesta ja sitä kautta juoksun taloudellisuuden ja muscle power:n paranemisesta.

Tämän tutkimuksen yhteenvetona voidaan todeta, että hermo-lihasjärjestelmän voimantuotto-ominaisuudet ovat tärkeitä kestävyyssuorituskykyä selittäviä tekijöitä ja että MART:n maksiminopeutta voidaan käyttää arvioitaessa kestävyysurheilijoiden hermo-lihasjärjestelmän toimintakapasiteettia. Lajinomaisella nopeus- ja nopeusvoimaharjoittelulla pystytään parantamaan kestävyysurheilijan voima-nopeusominaisuuksia, ja juoksun taloudellisuutta ja sitä kautta kestävyyssuorituskykyä. Tutkimuksen tulosten perusteella esitetäänkin hypoteettinen malli, joka huomioi kestävyysharjoittelun, kestävyysominaisuuksien ja taloudellisuuden lisäksi myös voima-nopeusharjoittelun ja hermo-lihasjärjestelmän toimintakapasiteetin kestävyyssuorituskykyä selittävinä tekijöinä.

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Appendix 1. The performance characteristics of two well trained subjects, A and B, with different 5-km run times and subjects C and D who had similar 5-km run times. VO_{2max} = maximal oxygen uptake, RCT = respiratory compensation threshold, RE = running economy, V_{MART} = maximal velocity of the maximal anaerobic running test, V_{20m} = maximal 20- m velocity on a track, 5K = 5- km time.

Subject	VO_{2max} (ml•kg^{-1}•min^{-1})	RCT (m•s^{-1})	RE_{track2} (ml•kg$^{-0.75}$•min^{-1})	V_{MART} (m•s^{-1})	V_{20m} (m•s^{-1})	5 K (min)
A	65	4.31	154	6.22	7.94	18.20
B	65	4.33	142	7.33	8.55	17.31
C	68	4.44	147	6.56	8.04	17.24
D	63	4.17	140	7.08	9.07	17.30

Appendix 2. The selected 20- m maximal run stride parameters and ground reaction forces of two well trained subjects A and B with different 5-km run times. CT = ground contact time, SR = stride rate, SL = stride length, Fz = vertical component of the ground reaction forces, Fy = horizontal component of the ground reaction forces

Subject	CT (ms)	SR (1/s)	SL (v/SR)	Braking phase (ms)	Propulsion phase (ms)	Braking Fz/kg	Propulsion Fz/kg	Braking Fy/kg	Propulsion Fy/kg
A (5K = 18.20 min)	137	3.75	2.12	64	73	23.96	14.97	4.06	3.59
B (5K = 17.31 min)	119	4.03	2.12	57	62	25.7	15.39	3.89	3.65

Appendix 3. The selected 5- km mean CVLs run stride parameters and ground reaction forces of two well trained subjects A and B with different 5-km run times. CT = ground contact time, SR = stride rate, SL = stride length, Fz = vertical component of the ground reaction forces, Fy = horizontal component of the ground reaction forces

Subject	CT (ms)	SR (1/s)	SL (v/SR)	Braking phase	Propulsion phase	Braking Fz/kg	Propulsion Fz/kg	Braking Fy/kg	Propulsion Fy/kg
A (5K = 18.20 min)	210	2.85	1.63	104	106	21.00	13.01	2.38	2.22
B (5K = 17.31 min)	183	2.85	1.65	90	93	22.09	14.04	2.61	2.19

Original papers

I

Treadmill and track running physiological responses as determinants of 10-km running performance

by

Leena Paavolainen, Keijo Häkkinen, Ari Nummela and Heikki Rusko

(submitted for publication)

II

Neuromuscular characteristics and fatigue during 10-km running

by

Leena Paavolainen, Ari Nummela, Heikki Rusko and Keijo Häkkinen

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III

Neuromuscular characteristics and muscle power as determinants of 5-km running performance

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IV

Muscle power and VO_{2max} as determinants of horizontal and uphill running performance

by

Leena Paavolainen, Ari Nummela and Heikki Rusko

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V

Explosive-strength training improves 5-km running time by improving running economy and muscle power

by

Leena Paavolainen, Keijo Häkkinen, Ismo Hämäläinen, Ari Nummela
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