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WITH SPECIAL REFERENCE TO DIFFERENT CONSTANT SPEEDS RANGING FROM SUBMAXIMAL TO SUPRAMAXIMAL

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Electromyographic (EMG) activity, force and anaerobic energy production
were investigated in male and female sprinters (n=41) running at dif-
ferent constant speeds ranging from submaximal to supramaximal. Supra-
maximal running was performed by a towing system. Cinematographic
analysis showed that both stride length (SL) and stride rate (SR) in-
creased ($p < 0.05-0.001$) with increasing running speed and the difference
($p < 0.001$) between men and women in maximal velocity was accompanied by a
significant ($p < 0.01$) difference in SL. In supramaximal running the in-
crease in velocity was associated with an increase ($p < 0.05-0.001$) in
either SL or SR. Neural activation (IEMG) of the leg muscles measured
with a telemetric system increased ($p < 0.05-0.001$) with increasing
running speed, being greater ($p < 0.001$) in the braking phase than in the
propulsion phase. Preactivity of the five leg muscles increased and
correlated positively and significantly ($p < 0.01$) with the average
resultant force in the braking phase with increasing speed. Higher
running speed was accompanied by increases ($p < 0.05-0.001$) in the
average resultant force during both contact phases except during the
propulsion phase of the highest test speeds. Force platform recordings
also showed that maximal and average forces in the braking phase were
greater ($p < 0.01-0.001$) during supramaximal than during maximal running.
Blood lactate and oxygen debt were significantly ($p < 0.05-0.001$) greater
for exercise and recovery following the maximal rather than the supra-
maximal runs, showing lower anaerobic energy production in supra-
maximal sprinting. On the basis of correlational analysis, it was
further concluded that in supramaximal running with a horizontal towing
system it is possible to run at a higher SR than in normal maximal
running. Preactivity increases stiffness in leg muscles, which is
needed to resist high impacts during the very first stages of contact.
Average net resultant contact force as a specific force indicator is
greater in men and is primarily related to SL; the values for this
indicator explain the differences in maximal running velocity between
men and women.

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CONTENTS

PREFACE

The present thesis is based on the following papers, which will be referred to by their Roman numerals:

I   MERO, A., KOMI, P.V. Effects of supramaximal velocity on biomechanical variables in sprinting. Int J Sport Biomech 1: 240-252, 1985.

II   MERO, A., LUHTANEN, P., KOMI, P.V. Segmental contribution to velocity of center of gravity during contact at different speeds in male and female sprinters. J Human Mov Studies 12: 215-235, 1986.

III MERO, A., KOMI, P.V. Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. Eur J Appl Physiol 55: 553-561, 1986.

IV   MERO, A., KOMI, P.V. Electromyographic activity in sprinting at speeds ranging from submaximal to supramaximal. Med Sci Sports Exerc, in press 1987.

V   MERO, A., KOMI, P.V., RUSKO, H., HIRVONEN, J. Neuromuscular and anaerobic performance of sprinters at maximal and supramaximal speed. Int J Sports Med 8: 55-60, Suppl 1, 1987.

1. INTRODUCTION

A large majority of physical activities require the rapid movement of the body from one place to another. Running belongs to these rapid forms of human locomotion. In its various forms, e.g. in sprinting, running is a basic skill and it is essential to the performance of a variety of sport activities. Several aspects of running have been studied since the beginning of the 1920's (see Amar 1920) when the first kinematic results of running were reported. Many reviews of the biomechanics of running (e.g. Atwater 1973, Dillman 1975, Williams 1985) have also become available during recent years. In the review of literature in the present investigation an effort is made to present the main results and conclusions according to the research available on technique, electromyographic activity, force production, neural factors, muscle structure and the energetics of running. In some areas of sprint running, information is very limited and therefore the literature is supplemented with information on slow running.

2. REVIEW OF LITERATURE

2.1. Technique of running

Running velocity is determined by a product of stride rate (SR) and stride length (SL). In studies where the same subjects ran at different speeds (Knuttgen 1961, Sinning and Forsyth 1970, Nelson et al. 1972, Hoshikawa et al. 1973, Luhtanen and Komi 1978) it has been shown that there is an increase in SR and SL with increasing speed. These increases seem to be primarily linear for speeds up to 7 m x s^{-1}, while at higher speeds there is a smaller increment in SL and a greater increment in SR for a given increase in velocity (see e.g. Luhtanen and Komi 1978). This means that at high speeds runners increase their velocity by increasing SR to a relatively greater extent than SL. Contradictory results were reported by Chapman and Caldwell (1983a). They examined changes in SR and SL of a single world-class female sprinter at high speeds ranging from 6.7 to 9.5 m x s^{-1} and noticed greater increases in SL at higher speeds than were found at lower speeds. In SR a concurrent drop was observed. In maximal sprinting of male sprinters it is suggested that SR has a more decisive role than does SL (e.g. Tabatschnik et al. 1978, Mero et al. 1981). The highest values of SR have been reported to be above 5 Hz (e.g. Tabatschnik et al. 1978) and SL has ranged from approximately 2 m to 2.5 m (e.g. Mero et al. 1982, Mann and Herman 1985). Conflicting results have been observed when comparing SL and SR between male and female runners (see e.g. Nelson et al. 1977, Elliott and Blanksby 1979a), but it is possible that the differences between these two studies might be caused by the different running speeds or different ability levels of the groups. There is, however, a lack of data for male and female

sprinters running at high speeds. The assumption that SL is
related to body size is supported in some, (see e.g. Cavanagh
et al. 1977, Elliott and Blanksby 1979a) but not all studies
(see e.g. Adrian and Kreighbaum 1973, Cavanagh and Williams
1982). In these studies the variability in body height and
leg length among subjects was similar, the speeds of running
were low and studies included overground and treadmill
running. Hoffmann (1964) conducted an extensive study of
sprint running analyzing 56 of the top male sprinters in the
world. The correlations between maximal SL (measured between
the 50 and 60 m distance in the 100 m race) and the
variables of height and leg length were high (r = .59 and
.70, respectively). Similar relationships (r = .63 and .73)
were reported by Hoffmann (1967) also for 23 world-class
female sprinters. So there seems to be sufficient data to
support the statement that a strong relationship exists
between SL and height and leg length in maximal sprinting of
both sexes. Supramaximal running velocity has been used in
sprint training in order to increase SR. Different methods
such as back-wind, downhill running (e.g. Leierer 1979),
towing horizontally (e.g. Bosen 1979), towing both
horizontally and vertically (e.g. Glaspey 1980) and high-
speed treadmill running (Singh et al. 1976) have been
employed to attain supramaximal running speeds. However,
there are no published research results available to demon-
strate the precise interaction of SR and SL between supra-
maximal and maximal runs.

The sum of contact and flight times equals the time of a
stride. Since the stride time usually decreases with an in-
crease in running speed (e.g. Kurakin 1972, Saito et al.
1974), one or both of these phases must contribute in some
manner to the decrease in stride time. Several researchers
(e.g. Amar 1920, Högberg 1952, Elliott and Blanksby 1976)
have found that flight time becomes slightly longer as
running velocity increases. However, Kurakin (1972) reported
a curvilinear relationship between flight time and running
velocity. He reported that flight time initially increased

with velocity and subsequently decreased at the higher
speeds. In maximal sprinting flight time has ranged from
approximately 0.120 s to 0.130 s (e.g. Kunz and Kaufmann 1981,
Mero et al. 1982). Contact time has been reported to decrease
significantly as running velocity is increased (e.g. Amar
1920, Kurakin 1972, Nelson et al. 1972, Bates and Haven 1974,
Chapman and Caldwell 1983a). Luhtanen and Komi (1978)
divided the contact phase into eccentric and concentric
phases, which they defined as the time period when the centre
of gravity of the body moved either downward (eccentric) or
upward (concentric). Relative times for both phases decreased
similarly across a speed range of 3.9-9.3 m x s^{-1}. The
eccentric phase occupied approximately 34 per cent of
contact time. In maximal sprinting the contact time has been
very short ranging from about 0.080 s to 0.100 s (e.g. Kunz
and Kaufmann 1981, Mero et al. 1982).

Much research work has been done with joint angles of
the contact and swinging leg in running. Concerning thigh
angles it has been clearly shown how they vary throughout
the running cycle in slow running (e.g. Cavanagh et al. 1977,
Elliott and Ackland 1981, Ito et al. 1983) and in sprint
running (e.g. Kunz and Kaufmann 1981, Frishberg 1983, Mann
and Herman 1985). Critical points at the hip joint have
been the extension at toe-off and the flexion (knee lift)
during the swing phase.

Also knee angles during the running cycle have been
clearly described in the literature (e.g. Sinning and
Forsyth 1970, Bates et al. 1978, Bates et al. 1979, Elliott
and Blanksby 1979b). The contact knee angle has generally
been measured at foot impact, at toe-off and at its minimum
during the contact phase (maximum knee flexion). During the
swing phase maximal knee flexion has been shown to increase
with increased running speed. The advantages of such changes
are a decreased moment of inertia of the lower extremity
about the hip joint and thus less resistance to hip flexion
(e.g. Grillner et al. 1979).

Less data are available describing the angles of plantar

flexion and dorsiflexion at various phases of the running
cycle. It is also difficult to compare the results because
several different landmarks have been used to define ankle
angle. Also the ankle angle has generally been measured at
the beginning of the ground contact, at its minimum during
the contact phase and at toe-off. The position of the foot
at impact may have an influence on the subsequent plantar
flexion, and runners can be classified as rearfoot, midfoot
or forefoot strikers depending upon the general area of the
foot that makes first ground contact (e.g. Kerr et al. 1983).
In maximal sprinting top runners are mostly forefoot
strikers (e.g. Mero et al. 1982).

Vertical peak-to-peak displacement of the centre of
gravity of the body during stride has been shown to decrease
with increased running speed (e.g. Cavagna et al. 1971,
Luhtanen and Komi 1978). The latter researchers noticed dis-
placements of 0.109, 0.086, 0.070 and 0.067 m for speeds of
3.9, 6.4, 8.0 and 9.3 m x s^{-1}, respectively. In the study by
Mero et al. (1982) vertical displacements were 0.047, 0.050
and 0.062 m for "good" (9.86 m x s^{-1}), "average" (9.60
m x s^{-1}) and "poor" (9.24 m x s^{-1}) male sprinters, respec-
tively. The comparison of the vertical movements of the
total body with those of the total body minus arms showed,
within a speed range from 3.8 to 5.4 m x s^{-1}, a 0.005 m
greater displacement when the arms were included than when
they were not (Hinrichs 1982). However, the arms slightly
reduced the movements of the centre of gravity of the body
in the anteroposterior and mediolateral directions. The
results of a kinetic analysis of sprinting by Mann (1981)
indicated that the role of the arms is to maintain balance.
Some researchers have considered that an erect posture is a
good running form (e.g. Slocum and Bowerman 1962). However,
most of the researchers have found that runners lean
slightly forward throughout the cycle. In sprinting about
10-16 degrees of trunk lean have been reported for constant
maximal velocity (e.g. Mero et al. 1982, Frishberg 1983).

A number of studies have described that at constant

speed there is a decrease in velocity of the centre of
gravity of the body following initial foot impact. Then,
during the propulsion phase, there is an increase in veloci-
ty. Cavanagh and LaFortune (1980) found a decrease at 0.18
m x s^{-1} in running velocity during the braking phase at
4.47 m x s^{-1}. It was followed by an increase of 0.27 m x s^{-1}
during the propulsion phase. The speed at toe-off was
greater than that at touchdown. The researchers hypothesized
that the effects of air resistance would probably account
for the decreases in running velocity during flight which
would maintain a constant average running velocity. In
maximal running of male sprinters, Mero et al. (1982)
reported decreases of 0.39 m x s^{-1} for "good" sprinters,
0.43 m x s^{-1} for "average" sprinters, and 0.53 m x s^{-1} for
"poor" sprinters. The reason for the decrease in running
velocity is the horizontal distance between the first contact
point and the centre of gravity of the body at touchdown
(e.g. Deshon and Nelson 1964, Kunz and Kaufman 1981, Mero et
al. 1982). During this distance the centre of gravity of the
body moves downward and horizontal running velocity
decelerates. This is a critical point in stride structure
for reasons of economy of running. There is no information
available in the literature concerning stride structure and
economy of supramaximal running.

2.2. Electromyographic activity of running

Running requires a complex series of activation of the
musculature in the body. The electromyographic (EMG) ac-
tivity of the muscles has been studied especially in slow
running. In leg muscles EMG activity has generally been
found to increase with increasing running speed (Hoshikawa
et al. 1973, Elliott and Blanksby 1979c). Ito et al. (1985)

observed that average integrated EMGs summed from six leg
muscles remained constant for the contact phase over a speed
range of 3.7-9.3 m x s^{-1}. In the flight phase EMGs, however,
increased with running speed. It was suggested that the lack
of increased EMG activity during contact at higher speeds
may be related to increased recoil of elastic energy (see
e.g. Cavagna et al. 1971, Luhtanen and Komi 1980, Williams
and Cavanagh 1983) during the concentric phase. The increased
muscular activation would not be needed. Komi (1983) found
greater muscle activity during the eccentric phase than
during the concentric phase of contact.

EMG activity has been found to increase in the hamstring
muscles at touchdown in slow running (e.g. Elliott and
Blanksby 1979b,c). Subsequently extension of the hip takes
place and an increase in the hamstring EMG occurs. Simulta-
neously it has been observed also high activity in the
rectus femoris (RF), and during the late contact phase the
activity of the muscles had decreased (Elliott and Blanksby
1979b,c). The only small amount of activity in the RF during
the early part of swing suggests that this muscle was not a
prime factor in hip flexion. Other hip flexors, which were
not measured, were probably active in causing hip flexion.
At the end of the swing phase the activity of the hamstring
muscles increases to slow the flexion at the hip and sub-
sequently to begin the backward rotation of the leg in
preparation for foot impact (Elliott and Blanksby 1979b,c).

In slow running, increased EMG activity has been found
in the vastus lateralis (VL) and the vastus medialis (VM)
muscles at the beginning of contact. During early contact
the VL, VM and RF muscles show their greatest EMG activity
and it decreases at the end of the contact phase (e.g.
Brandell 1973, Elliott and Blanksby 1979b,c). During the
early part of the swing the knee flexes. This is mostly
passive, resulting from the transfer of energy into the
lower leg (Chapman and Caldwell 1983b) due to the flexor
activity occurring at the hip (Elliott 1977, Elliott and
Blanksby 1979b,c). According to the latter studies there was

slight simultaneous EMG activity in the hamstring muscles and before impact there was an increased activity in the quadriceps and hamstring muscles.

In slow running it has been reported that there is co-operation between the tibialis anterior (TA) and the triceps surae (TS) muscles at touchdown. It is thought to establish a stable base of contact (Elliott and Blanksby 1979b,c). The different positions of the foot at contact may affect TA activity but there is a lack of information in the litera-ture. In the braking phase high muscle activity of the TS has been found (Dietz et al. 1979, Elliott and Blanksby 1979b,c) and it continued to increase in the propulsion phase in slow running (Elliott and Blanksby 1979b,c) but decreased in sprinting (Dietz et al. 1979). During the flight phase there was only a small amount of activity in the TA when the foot was put in a dorsiflexed position for contact with the ground in slow running (Elliott and Blanksby 1979b,c). In sprinting, however, there was high activity in the TS and TA muscles before contact (Dietz et al. 1979).

EMG activity pattern in slow running seems to be quite well described in the literature but there is a need for research with highly skilled sprinters to understand better the various mechanisms of coordination during fast running including running at supramaximal speed.

2.3. Force production of running

There has been great interest in the ground reaction forces and body segmental contribution to force production during the contact phase. Researchers have used many variables to analyze force-time curves during the ground phase (see e.g. Bates et al. 1983). In the vertical ground reaction force

there are two distinct peaks during the impact and push off phases by rearfoot strikers (e.g. Cavanagh and LaFortune 1980, Nigg et al. 1981, Payne 1983, Bates et al. 1983). The impact peak is decreased or absent for midfoot or forefoot strikers (e.g. Cavanagh and LaFortune 1980, Clarke et al. 1983, Payne 1983). Also other factors such as running speed, type of footwear, and surface, may affect this peak (Nigg et al. 1981, Nigg 1983, McMahon and Greene 1979). Vertical ground reaction forces increase with increasing running speed. The impact peak ranged from 1.6 BW (body weight) at 3.4 m x s^{-1} to 2.9 BW at 5.4 m x s^{-1} and the second peaks were slightly higher than initial peaks (Roy 1982). These results were measured using non-athletes as subjects. Payne (1983) studied fast running and found a high impact peak of approximately 5.5 BW during sprint running (a single subject; average velocity of 9.50 m x s^{-1}). The subject made contact with the rearfoot first. Most sprinters, however, make the first contact high on the ball of the foot and this tends to cushion out the so called "heel spike".

Also peak horizontal force seems to increase with increased running speed (e.g. Roy 1982, Ito et al. 1983). Peak braking force increased from 0.5 to 0.8 BW and peak propulsion force from 0.3 to 0.5 BW for speed changes from 3.4 to 5.4 m x s^{-1} (Roy 1981). Payne (1983) noticed somewhat greater forces for a sprinter (approximately 1.1 BW and 0.6 BW, respectively). In mediolateral forces Roy (1982) found only small changes with increasing speed. Typical values are less than 0.3 BW (Cavanagh and LaFortune 1980, Roy 1982).

The movements of the body segments determine ground reaction forces. Hinrichs (1982) examined how the various body segments (the arms, legs, and trunk) affect them by measuring the relative inertial forces of the segments. He had 21 subjects running at 3.8 m x s^{-1}. The arms contributed 5 per cent to vertical forces, the trunk -3 per cent (reducing force), and the legs about 98 %. Contributions to horizontal force production were more complex. It was, however, obvious that the arms contributed little. Mero et al.

(1986a) showed that in the braking phase of maximal running
(9.57 $\pm$ 0.40 m x s^{-1}) negative horizontal force was pro-
duced by contact leg, arms and head-trunk. In the propulsion
phase negative horizontal forces were produced by swinging
leg and arms. All vertical forces were positive and in the
braking phase also swinging leg and in the propulsion phase
contact leg and head-trunk produced positive horizontal
forces.

The contribution of the body segmental velocities to the
velocity of the centre of gravity has been examined in
hurdling (Kollath 1983), but there is a lack of information
with regard to sprinting. The force production during supra-
maximal running and the relationship between running veloci-
ty and force production in maximal sprinting are also not
known exactly. Their investigation would therefore conform
to both scientific and practical interests.

The stretching of activated muscle (eccentric phase)
modifies the condition of the muscle, so that in the sub-
sequent concentric contraction the force output may be
enhanced. This phenomenon - elasticity - has been investi-
gated with isolated animal muscle (Cavagna et al. 1965) and
with intact human muscles (e.g. Cavagna et al. 1968). There-
fore the storage and recoil of elastic energy can be a major
contributor to the power involved in running (see e.g.
Cavagna et al. 1964, Cavagna et al. 1971). In the concentric
phase of muscles during running power would be generated
both by the concentrically contracting muscles and the
recoil of elastic energy (see also Bosco et al. 1982).
Luhtanen and Komi (1980) evaluated the elasticity of the
contact leg from film data using an apparent spring constant
value. It is great when the resultant force at the centre of
gravity is great, the peak-to-peak oscillation and the
horizontal displacement of centre of gravity are small and
the contact time is short. In running (1.9-6.1 m x s^{-1}) the
contribution of stored elastic energy to positive (concen-
tric) work has been shown to increase with speed (Ito et al.
1983) and it has been thought to play an important role in

maintaining high mechanical efficiency of positive work. However, the role of elasticity in sprinting at high speeds especially in supramaximal running is not yet known exactly.

2.4. Neural factors in running

In voluntary contractions the central nervous system regulates muscle force by changing the number of recruited motor units. Additional force regulation is achieved by varying the individual motoneuron firing rates. In human locomotion the existence of EMG activity before contact, i.e. preactivation, has been described e.g. in stepping and hopping (Melvill Jones and Watt 1971) and in sprinting (e.g. Dietz et al. 1979). This phenomenon means also the increase of muscle stiffness (see e.g. Nichols and Houk 1976) for preparation of the impact loads. EMG recordings during falls have indicated that in those muscles involved in landing, a significant increase in EMG appears shortly after ground contact (Dietz and Noth 1978a,b, Greenwood and Hopkins 1976), corresponding to a short latency spinal stretch reflex. It has been shown to exist also in human running (velocity of 7.90 m x s^{-1}, Dietz et al. 1979). Frigo et al. (1979) studied the relationship between muscle activation and muscle length and reported that maximal excitability occurred when the muscles were near their optimal length (the length where maximal force could be generated). In order to identify EMG activities of individual muscles during actual eccentric and concentric phases it is necessary to know the instant length of the respective muscles. This kind of method would give more exact information as compared to the conventional method (eccentric and concentric phases according to the vertical movement of the centre of gravity or to the negative and positive horizontal forces during contact).

In addition, EMG measurements could be used for indirect
evaluation of economy of running performance. Neural ac-
tivation can be utilized because energy expenditure (VO_2
consumption) is often difficult to measure during normal
sprint running on the track and also on the treadmill. There
is convincing evidence that EMG activity and energy ex-
penditure are related to each other (Bigland-Ritchie and
Woods 1976).

The relaxation period is triggered by the cessation of
neural activity to the muscles followed by the uptake of
calcium ions by the sarcoplasmic reticulum. In running the
contact and flight phases alternate and this suggests that
muscle contraction and relaxation phases take place in fast
sequences, especially in maximal sprinting. In order to in-
crease SR in sprint running both optimal muscle contraction/
muscle relaxation ratio and optimal motor coordination are
required. Some practical tests of motor coordination have
been used and on a tapping test differences have been found
between elite sprinters and controls, with the elite
sprinters performing the test better (Radford and Upton
1976, Mero et al. 1981).

2.5. Muscle structure and running

Skeletal muscle is known to be an extremely heterogenous
tissue. Two main groups of motor units exist, slow (type I)
and fast (type II) motor units which have functionally and
structurally different kinds of α-motoneurons. The motor
units which contain the respective different kinds of muscle
fibres, have been classified according to their contraction
time and their fatigue resistance (see Eberstein and Good-
gold 1968, Garnett et al. 1978). The myosin ATPase method
(Padykula and Herman 1955) have been used for identifying

the type I and type II fibres (Gollnick et al. 1972). The
latter study and also other studies (Costill et al. 1976,
Thorstensson et al. 1977, Mero et al. 1981) have shown that
sprinters have a high percentage of type II fibres in their
leg extensor muscles. Significant correlation coefficients
have also been shown between general force production and
speed of shortening and distribution as well as the relative
area of type II fibres in the contracting muscle (e.g.
Thorstensson et al. 1976, 1977, Green et al. 1979, Ivy et al.
1981, Mero et al. 1981). It would therefore be interesting
to examine more relations between ground reaction forces,
running velocity and muscle fibre characteristics.

2.6. Energetics of running

In short-term maximal exercises like sprinting the genera-
tion of energy in the muscles of the athlete occurs
primarily anaerobically, i.e. without the use of oxygen. In
skeletal muscle only two fuels provide energy anaerobically,
creatine phosphate and glycogen. Adenosine triphosphate
(ATP) can be regenerated from adenosine disphosphate (ADP)
by the direct transfer of phosphate from creatine phosphate
in a reaction catalyzed by creatine kinase. Glycogen, which
is a store of glucose within the muscle, is converted by
glycolysis into lactate, which regenerates 3 ATP molecules
for every glucose molecule used. This process generates
about 10 times less ATP than complete oxidation of glucose
to carbon dioxide and water, but the capacity of the process
is high especially in type II muscle fibres (e.g. Essén et
al. 1975). The high-energy phosphate concentrations were
generally comparable between type I and type II fibres, but
women had more creatine phosphate in type I than in type II
fibres (Rehunen and Härkönen 1980). The subjects of the

particular study were male and female volunteers (non-
athletes, 18-26 years). In the other study by Rehunen et al.
(1982) fourteen sprinters (including three women) and 11
male long-distance runners served as subjects. The exercises
of maximal intensity used were either light (3 x 40 m, rest
periods 5 min; 20 m + 40 m + 60 m, rest periods 30 s) or
extremely exhaustive (3 x 300 m, rest periods 5 min and 3
min). The results suggested that during short-term exercise
type II muscle fibres consume more of their creatine
phosphate stores than type I fibres. In vigorous exercise,
sprinters are able to recruit not only type II but also type
I muscle fibres, and in such trained sprinters creatine
phosphate is possibly resynthesized more rapidly in type II
than in type I muscle fibres. Those findings also support
the recruitment order where very high threshold motor units
are activated first (see e.g. Grimby and Hannerz 1968, 1977,
Gydikov and Kosarov 1974). This order is a reversal of
Henneman's "size principle" (Henneman et al. 1965a,b) and
would mean that in fast voluntary movement such as maximal
sprinting type II fibres are the first to be engaged in con-
traction. It must be admitted, however, that the mechanism
is still speculative, and some reports (e.g. Burke 1986)
have suggested alternative recruitment orders.

It is likely that, for the first 2-3 s of maximal sprint,
creatine phosphate provides most of the energy for re-
generation of ATP but then anaerobic glycolysis gradually
takes over so that by 5 s the latter process provides
almost all the energy (Newsholme 1984). This is supported by
the study of Jacobs et al. (1983). They found that pronounced
lactate accumulation occurs during maximal exercise of 10-s
duration using a bicycle ergometer. Support is also given by
Kindermann and Keul (1977) with blood lactate measurement
following a 100 m sprint race (10.52 s, blood lactate
13.15 ± 1.85 mmol x l^{-1}).

There is always an oxygen debt after exercise (oxygen
debt = total oxygen uptake minus resting oxygen uptake).
Several variables are involved in the delayed return of

oxygen uptake during recovery to the basal level. Approximately 2-2.5 liters of oxygen is required by blood, myoglobin, elevated tissue temperature, adrenalin concentration, and cardiac and respiratory functions. ATP and creatine phosphate demand approximately 1-1.5 liters of oxygen. Therefore, up to 4 liters of the oxygen debt may be alactacid, i.e., it is not involved in the handling of lactic acid. The remainder of the total oxygen debt after heavy exercises is lactacid (e.g. Margaria et al. 1933, Margaria 1967). Oxygen debt following a maximal sprint run of 400 m may reach as high as 20 liters measured during 60 min recovery (Karlsson et al. 1972).

Energetics of sprint running is quite well described by the recent studies but to the best of the present researcher's knowledge there are no results available concerning supramaximal sprints. Therefore, it would be interesting to compare the energetics of maximal and supramaximal sprint running.

3. PURPOSE OF THE PRESENT INVESTIGATION

Available knowledge of running is quite extensive, especially with regard to slow running. However, there is a clear lack of information on sprint running, which gave rise to the present series of experiments. The detailed purposes of this investigation were:

(1) to examine how SL and SR change with increasing running speed in males and females, and what the precise inter- action of SL, SR and other technique variables is between maximal and supramaximal running;

(2) to study the body segmental contribution to horizontal velocity of C.G. during contact of different running speeds;

(3) to examine the EMG activity of various muscles during the stride cycle of sprint running with increasing speed and to find out possible relationships between EMG activity and contact forces and running velocity;

(4) to investigate the force-, and elasticity-velocity relationships at different running speeds and the possible relations between muscle fibre characteristics and force production in maximal running; and

(5) to compare anaerobic energy production following maximal and supramaximal running

4. RESEARCH METHODS

4.1. Subjects

A total of 41 subjects were studied. They were male (n=25) and female (n=16) sprinters and Table 1 summarizes their physical characteristics, age and running records in each paper. The determination of muscle fibre distribution and muscle fibre area ratio has been described in section 4.3.7. All subjects were highly skilled and many of them had participated in the Olympic Games, in World Championships, in European Championships or in European Junior Championships in sprint events between 1979 and 1984.

4.2. Statistical methods

Statistical methods included the mean ($\bar{x}$), standard deviation (SD), standard error of the mean (SE) and linear correlation coefficient (r). The statistical significance of differences was tested by means of Student's two tailed t-test for paired and unpaired samples and analysis of variance. Such calculations were carried out by using the "Statistical Package for the Social Sciences" (SPSS) programme (see Nie et al. 1975).

The accuracy of the methods used has been evaluated including error of measurement. The reproducibility of the measurements was conducted on duplicate analysis and expressed as a correlation coefficient and a coefficient of variation (C.V.).

TABLE 1. Mean (± SD) of the physical characteristics, age and running records of the subject groups

Subject groups	n	Age (y)	Height (m)	Mass (kg)	Fat[a] (%)	Muscle[b] fibre distribution Type II (%)	Type IIA (%)	Type IIB (%)	Muscle[b] fibre area ratio TypeII:TypeI	100 m record[c] (s)
Paper I										
Men A	7	21.1±3.1	1.83±0.06	77.2±6.4	10.3±0.9	58.2±3.1	35.9±4.0	22.3±7.1	1.48±0.20	10.57±0.16
Men B	6	20.0±1.0	1.78±0.05	70.5±8.8	14.3±1.6	58.3±12.2	37.3±7.4	21.0±5.1	1.00±0.04	11.15±0.24
Women A	2	26.2±0.7	1.68±0.03	60.5±0.4	19.9±0.0	-	-	-	-	11.15±0.02
Women B	7	18.3±1.4	1.67±0.05	56.7±3.7	24.0±2.0	54.3±13.8	34.1±4.4	20.2±9.9	1.20±0.11	12.18±0.26
Paper II										
Men	11	19.8±2.2	1.80±5.0	72.8±7.5	12.8±2.4	-	-	-	-	10.84±0.29
Women	7	20.1±3.6	1.67±5.0	57.5±4.1	23.3±2.5	-	-	-	-	11.95±0.50
Papers III and IV										
Men A	5	22.3±2.0	1.83±0.06	76.2±4.8	10.3±1.3	59.6±3.9	-	-	1.22±0.20	10.62±0.04
Men B	6	20.9±2.8	1.84±0.07	72.6±9.0	10.8±1.7	52.8±6.9	-	-	1.05±0.26	10.96±0.19
Women	8	19.9±2.8	1.69±0.06	58.9±6.9	19.8±1.9	56.3±10.3	-	-	0.96±0.28	12.22±0.28
Paper V										
Men	9	25.5±2.2	1.81±0.05	73.7±4.2	8.7±2.0	-	-	-	-	10.79±0.21

a   estimated from the skinfold measurements (Durnin and Rahaman 1967)

b   vastus lateralis

c   times are electrical times

4.3. Procedures, data collection and analytical methods

During the present investigation there were three measure-
ments and Figure 1 summarizes the experimental procedures in
each of them.

4.3.1. Runs and towing systems

Runs in the various measurements have been presented in
Table 2. They were carried out on a Tartan type track in an
indoor hall (air temperature 18-19$^{\text{O}}$) at the beginning of the
competitive season. In the first measurements in 1981 there
were seven runs and recovery periods between them were from
5 to 7 minutes. Running velocity was measured from a flying
start over 10 m (time was controlled by photocells during
measurements; the exact velocity was calculated from the
film). Supramaximal runs were performed by a horizontal
towing system (Figure 2A). The rubber rope was fastened to
both runners near the point of centre of gravity. The
assistant runner then tightened the rope and towed the
experimental runner to the supramaximal velocity. The
draught was uniform and its average force was 30-45 N as
measured with a strain gauge system. The subjects were in-
structed to run as fast as possible but with normal relaxed
technique. All the subjects (as in other measurements also)
were accustomed to the towing method through their previous
training experiences and they ran supramaximal as also other
runs using their normal track shoes with spikes. In the
second measurements in 1983 all subjects ran twice at five
different speeds from submaximal 1 (52.7 %) to supra-
maximal (108.4 %) level. The testing procedures were other-
wise similar to those in the first measurements. In the third
measurements in 1985 the subjects ran ten sprints at maximal
or supramaximal speed. The recovery between repetitions was
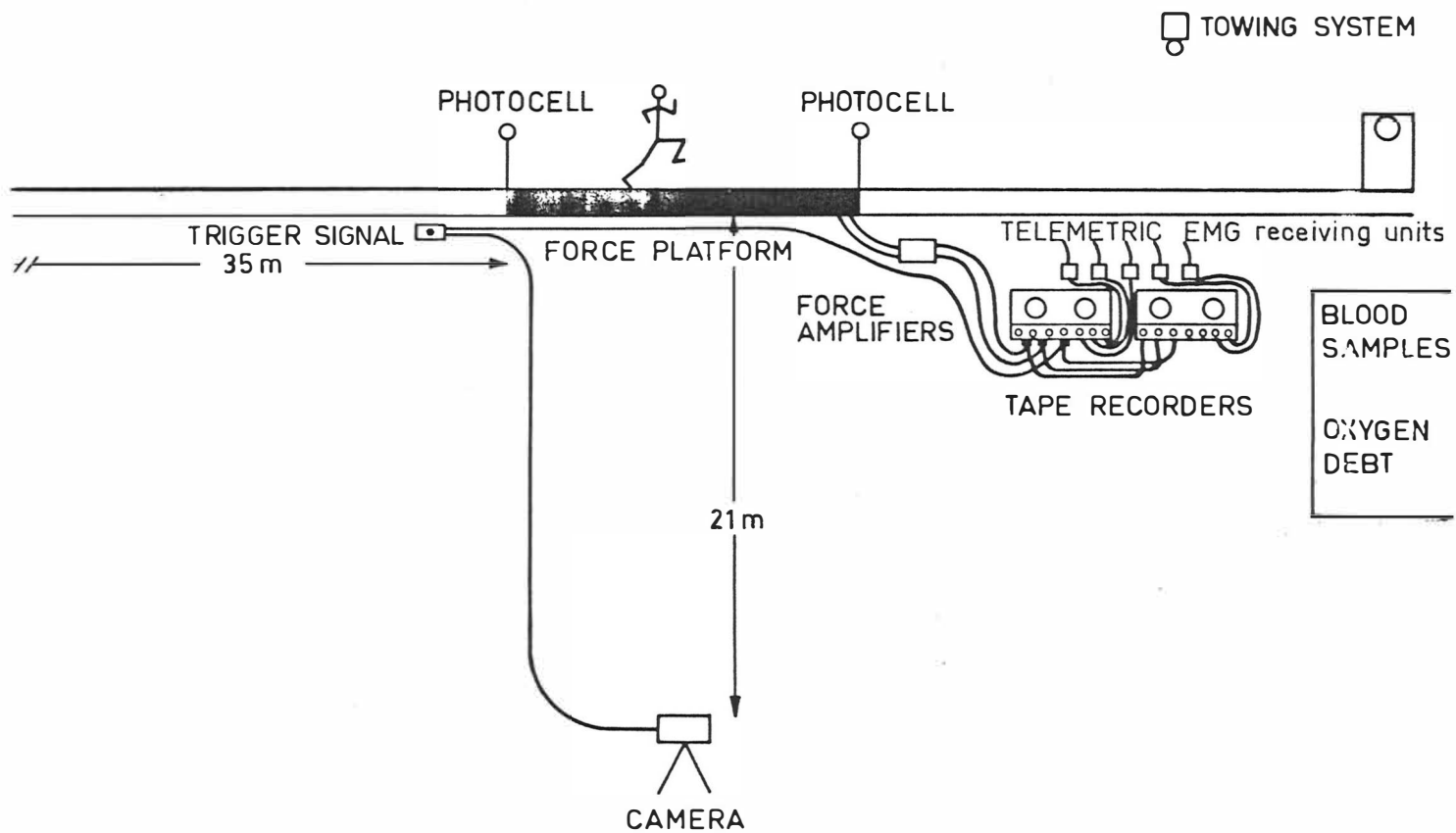
FIGURE 1. Schematic presentation of the experimental procedures (for details of the towing system, see Figure 2B)

TABLE 2. Runs in the various measurements

Measurements		
I	II	III
(papers I and II)	(papers III and IV)	(paper V)
Warm up	Warm up	Warm up
2 x submaximal	2 x submaximal 1	3 x maximal
2 x maximal	2 x submaximal 2	3 x supramaximal
2 x supramaximal	2 x submaximal 3	2 x supramaximal
1 x maximal	2 x maximal	2 x maximal
(posteffect)	2 x supramaximal	(posteffect)

5 minutes. Following the first three runs there was a 28-minute set recovery and following the next three supramaximal runs the set recovery was 24 minutes. Supramaximal speed was achieved by a resultant towing system where an electro-mechanical apparatus (Juhakoski Co, Jyväskylä, Finland) towed the runner by means of a rubber tope which was fastened to him near the point of centre of gravity (Figure 2B). The angle of draught ranged from 10 to 17 degrees from horizontal level in the phase where the analysis of running was made. A strain gauge system (weight 0.841 kg) which was fixed to a belt (weight 0.236 kg) of the runner measured the force of draught and it was sent telemetrically to magnetic tape (Racal Store 7). The basic force of draught ranged from 24 N to 26 N and the peak force respectively from 62 N to 71 N. The peak force occurred in the braking phase of foot contact. Reproducibility of draught was satisfactory (C.V. = 1.9-3.1 %). A frequency apparatus (weight 0.255 kg) was fixed to another belt (weight 0.251 kg) which was on the shoulders of the runner at supramaximal speed. According to information on the physical characteristics of the subjects a signal frequency of about 110 % of the supposed stride rate was chosen in advance and the apparatus sent an audiogram into the ears of the runner. The real percentage value of

34
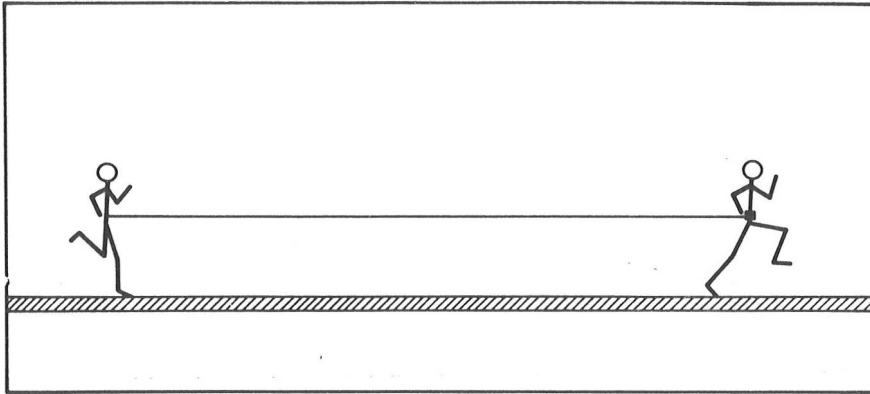
FIGURE 2A. Horizontal towing system
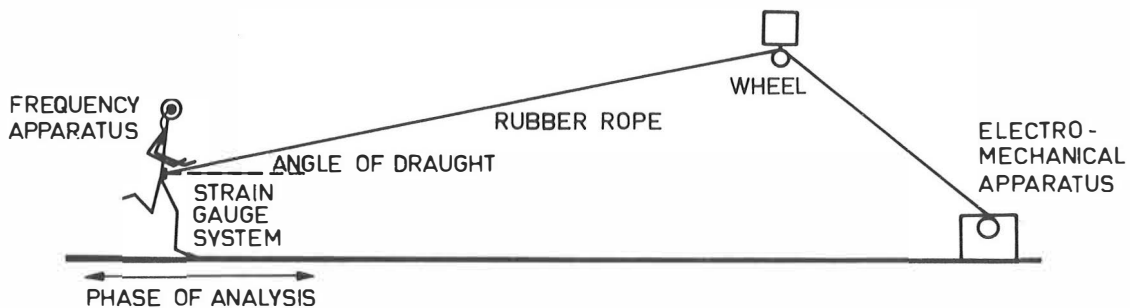
FIGURE 2B. Resultant towing system

frequency was 109.0 $\pm$ 1.6 % of the analyzed stride rate at supramaximal speed. The total extra load of the runner was 0.981 kg (one belt and EMG material) at maximal speed and 2.328 kg at supramaximal speed.

4.3.2. Film analysis

The runs were filmed with a Locam 51-0003 camera set to operate at 100 frames per second. The films were taken per-

pendicularly to the running direction during the phase of
uniform speed when the subject had accelerated 35 m. The
stride cycle covering the contact and flight phases (Figure
3) was analyzed using a Vanguard and a Lafayette film
analyzer, Summagraphics 10, Data Tablet/Digitizer, and
HP 21 MX computer. Based on the standards provided by
Dempster (1955), the mechanical model of the runner was
assumed to consist of 14 rigid body segments. The segmental
landmarks were marked on the skin with black ink. The
equations of joint landmarks for segmental movements were
smoothed via 9th-degree polynomial curve fitting (Kuo
1965). Velocities and acceleration were derived from these
equations. The contact phase was divided into braking
(eccentric) and propulsion (concentric) work phases
according to the vertical movements of the centre of gravity
(CG) during foot contact.
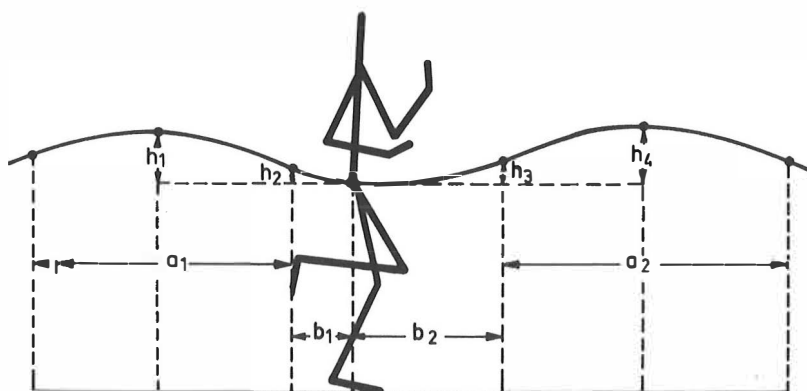
FIGURE 3. Variables of the path of the centre of gravity
during the running cycles. $a_{1,2}$ = horizontal dis-
placement during flight phase, $b_{1,2}$ = horizontal
displacement during contact phase (1 = braking
phase, 2 = propulsion phase), h_{1-4} = vertical dis-
placement

The segmental contribution to velocity of CG in the phases of maximal deceleration and acceleration (Figure 4) was calculated using the following formulae (paper II):

$$\bar{p} = m\bar{v} \tag{1}$$

$$\bar{p}_i = m_i\bar{v}_i \tag{2}$$

$$m\bar{v} = m_1 \cdot \bar{v}_1 + m_2 \cdot \bar{v}_2 + \ldots m_i \cdot \bar{v}_i \tag{3}$$

where $\bar{p}$ = momentum of the total body, $\bar{p}_i$ = momentum of the segment i, m = mass of the total body, m_i = mass of the segment i, $\bar{v}$ = velocity of the total body, $\bar{v}_i$ = velocity of the segment i.

The role of the different body segments during foot contact (paper II) was evaluated using the equivalence of force impulse, $\int_0^t \bar{F}_i(t)dt$, and the change of linear momentum. $m_i(\bar{v}_{2_i} - \bar{v}_{1_i})$, in the horizontal direction:

$$\int_0^t \bar{F}_i(t)dt = m_i(\bar{v}_{2_i} - \bar{v}_{1_i}) \tag{4}$$

where $\bar{F}_i(t)$ = force of the segment i, t = duration of phase, m_i = mass of the segment i, $\bar{v}_{2_i} - \bar{v}_{1_i}$ = change of velocity of the segment i during phase.

Timing of the body segments was measured by calculating the time durations from touchdown to the points of maximal and minimal segmental velocities. The point of maximal segmental velocity was also used for estimation of the timing pattern (paper II).

Economy of running was evaluated (paper II) using the absolute and relative values of deceleration of velocity of CG in the braking phase.

The elasticity of the contact leg (paper III), which was used to express the combined elasticity of the mechanical system of the runner during the braking and propulsion phase, was evaluated from the film data using an apparent spring constant k (Luhtanen and Komi 1980). When x = 0, the leg has its minimum value, which is h - Δy l_i. Then the apparent spring constant is
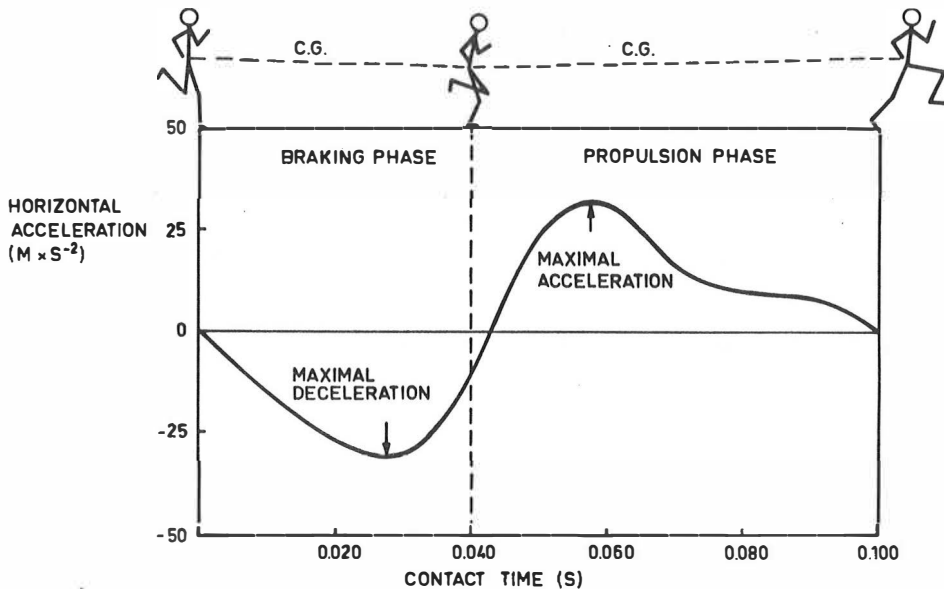
FIGURE 4. Phases of maximal deceleration and acceleration during contact

$$k_i = \frac{\pi\, mg\,(a_i + b_i)}{2b_i \left[\sqrt{h_i{}^2 + b_i{}^2} - (h_i - \Delta y\, l_i)\right]} \qquad (5)$$

where m = mass of subject, g = 9.81 m x s^{-2}, a_i = horizontal distance from contact to the highest point, b_i = horizontal distance from the lowest point to the beginning or end of contact, h_i = height of CG during the beginning and end of contact, $\Delta y\, l_i$ = vertical change of CG during contact.

The effect of the mass of subject was eliminated dividing the k_i value by the mass as follows:

$$k = \frac{k_i}{m} \qquad (6)$$

Instant length of the gastrocnemius muscle (paper IV) was calculated by the method described by Grieve et al. (1978). This method uses the angular variations in the knee joint and the ankle joint calculated from the film data as

follows:

$$\Delta L_i = A_0 + A_1(\theta_i) + A_2(\theta_i)^2 \tag{7}$$

where ΔL_i = the length change (in per cent segment length) attributed to angle θ_i, A_0 = -22.18468 for ankle and 6.46251 for knee, A_1 = +0.30141 for ankle and -0.07987 for knee, A_2 = -0.0061 for ankle and +0.00011 for knee.

The total change in muscle length is then

$$\Delta L = \Delta L_1 + \Delta L_2 \tag{8}$$

The reproducibility of the maximal and supramaximal runs was analyzed with duplicate measurements using 23 variables (paper I). In maximal runs the reproducibility was better (r = .81-.98; C.V. = 3.2-9.6 %) than in supramaximal runs (r = .70-.93; C.V. = 3.9-19.5 %).

4.3.3. Recording of reaction forces

A long (10 m x 1.2 m) force platform system (Komi 1985) was located in the middle of a level indoor straightway (35-45 m) (papers III-V). The subjects ran on this force platform (covered with Tartan mat) when filming was carried out. Force-time curves of the horizontal and vertical ground reaction forces were stored on magnetic tape (Racal Store 7). Averaged data of two right foot contacts for each subject at every speed were analyzed using a computer system (HP-1000). The contact phase was divided into braking and propulsion phases according to the negative horizontal force. The difference of the contact times compared to the film analysis data was 8.8 $\pm$ 2.6 % (paper III). In the same paper (III) the reproducibility of the forces was analyzed with duplicate measurements at maximal speed. For the average resultant force in the propulsion phase the reproducibility

was better (r = .92; C.V. = 5.1 %) than for the braking phase (r = .89; C.V. = 7.3 %).

4.3.4. Electromyographic recordings

Electromyographic (EMG) activity was recorded telemetrically (Medinik AB Model 1C-600-G) using bipolar surface electrodes (Beckman miniature sized skin electrodes) with a constant interelectrode distance of 20 mm. The electrodes were fixed over the muscle bellies of the right side of the body and were placed longitudinally over the motor point areas determined by an electrical stimulator (DISA). EMG signals were amplified with preamplifiers (1 Hz - 1 kHz) and stored simultaneously with the force on magnetic tape. Off-line EMG analyses (IEMG for 1 s) of two ipsilateral foot contacts (the same as for forces), two contralateral foot contacts, and flight phases between them were performed using a HP-1000-F computer system. The sampling frequency employed in the analog-to-digital conversion was 1000 Hz (as it also was for forces).

In the third paper (III) EMG activity was analyzed from the vastus lateralis (VL) and gastrocnemius cap. lat. (GA) muscles during braking and propulsion work phases (according to horizontal forces).

In the fourth paper (IV) two series of runs were analyzed. During the first series EMG activity was recorded simultaneously from the m. gastrocnemius cap. lat. (GA), biceps femoris cap. long. (BF), gluteus maximum (GM), rectus femoris (RF) and vastus lateralis (VL) of all the subjects (n=19) at each speed. The second series focused on the recording of EMGs from the m. tibialis anterior (TA), latissimus dorsi (LD), rectus abdominis (RA), biceps brachii (BB) and triceps brachii (TB) of the male subjects (n=10) at the three highest speeds. Analysis was made during the various phases of the stride cycle presented in Figure 5.
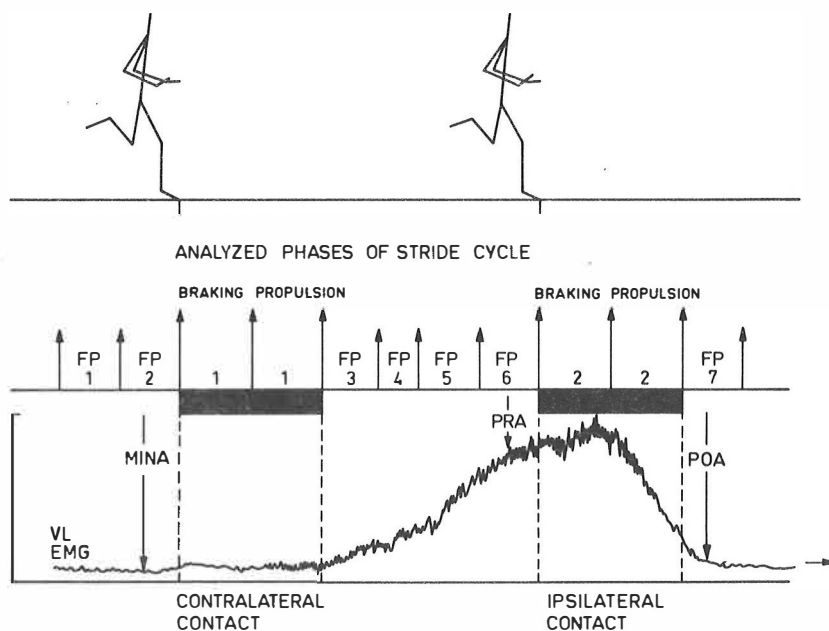
FIGURE 5. Analyzed phases of the rectified EMG during the
stride cycle (FP = flight phase, VL = m. vastus
lateralis, MINA = minimum activity, PRA = pre-
activity, POA = postactivity)

Flight phases 2, 3, 6 and 7 ($FP_{2,3,6}$ and 7) were 50 ms in
duration, FP_1 ranged from 23 ms (maximal) to 50 ms (sub-
maximal speeds 1 and 2), FP_4 ranged from 0 ms (maximal and
supramaximal speed) to 39 ms (submaximal speeds) and FP_5
ranged from 10 ms (supramaximal speed) to 50 ms (submaximal
speeds 1 and 2). Contralateral and ipsilateral contacts were
divided into braking (eccentric) and propulsion (concentric)
phases according to horizontal forces (see e.g. Miller 1983).
It must be emphasized that this division into "eccentric"
and "concentric" phases is not actually correct for
individual muscles and should be understood as an approxi-
mation for the purposes of describing the braking and
propulsion phases and their possible interaction with
muscular behavior. Preactivity (PRA) of the leg muscles was
measured in the phase of FP_6. Postactivity (POA) of the leg

muscles was calculated after ipsilateral contact (in FP_7)
and minimum activity (MINA) during the stride cycle was also
recorded. The three variables (PRA, POA and MINA) are
illustrated in Figure 5. The results were presented as
absolute and relative IEMG values. Percentage values were
calculated from the ipsilateral maximal contact IEMG value
of each speed.

In the fifth paper (V) EMG activity was recorded from
the VL, GA, BF, GM and RF muscles and analysis was made
during the phases presented in Figure 5.

Reproducibility was analyzed with duplicate measurements
at maximal speed (papers III and IV). In IEMG of the five
leg muscles (GA, RF, VL, GM and BF) during the stride cycle
the reproducibility was similar to that of all the other
muscles (TA, LD, RA, BB and RB; r = .85, C.V. = 9.4 % and
r = .86, C.V. = 9.7 %, respectively). The reproducibility of
IEMG was satisfactory but the values were, however, lower
than those in jumping performances (r = .94, Bosco 1982).
Reproducibilities of PRA (r = .90, C.V. = 6.9 %), MINA (r =
.86, C.V. = 7.1 %) and POA (r = .86, C.V. = 7.9 %) for the
five leg muscles were also relatively good as well as that
of MINA for the other muscles (r = .90 and C.V. = 6.6 %).

4.3.5. Blood lactate

Blood samples (100 µl) were drawn from the fingertip to
determine lactate concentration (Hohorst 1962) (paper V).
They were taken at rest, one minute after each of the first
six runs and during a long recovery also at the second,
fourth, sixth, nineth, twelveth and fifteenth minute to find
out peak recovery lactate concentration.

4.3.6. Oxygen debt

Oxygen debt was determined in the third measurements. Before
the first run pre-exercise metabolism data were collected in
a sitting position for 5 min by Beckman MMC Horizon Systems.
Immediately after the last of the three maximal runs (8 $\pm$
3 s after crossing the finish) the subjects were seated and
started to breath into the Beckman Systems for the following
18 min. Identical procedures were used to collect the
respiratory gases for both maximal and supramaximal runs
(after three supramaximal runs it lasted 10 $\pm$ 3 s to start
the collection of expired air). Metabolic measures were
determined in 15-s periods and the system was calibrated
before and after each measurement using gases analyzed by
Schollander apparatus.

4.3.7. Muscle biopsy

Muscle biopsies (papers I and IV) were obtained from the
right vastus lateralis muscle using the needle biopsy
technique of Bergström (1962). The myosin ATPase method
(Padykula and Herman 1955) was used for identifying the fast
twitch (FT or type II) and slow twitch (ST or type I) fibres
(Gollnick et al. 1972). FT fibres were grouped into the sub-
types of fast oxidative (IIA) and fast glycolytic (IIB)
(Dubowitz and Brooke 1973) (paper I). The average number of
analyzed muscle fibres per sample was in study I 472 $\pm$ 124
ranging from 209 to 827 and in study IV 438 $\pm$ 108 ranging
from 224 to 630.
The fibre area ratio (type II : type I) of every subject
was calculated from cross-sectional samples (myosin ATPase
staining) from 10 FT and 10 ST fibres. The sample on the
glass slide was reflected by a microscope (Prado Universal
10, Data Tablet/Digitizer), which was connected to an

HP 21MX computer. The representativeness of this type of subsample in the calculation of the fibre cell areas for the entire biopsy sample has been demonstrated to be relatively high with this summagraphics system (r = .90-.92, Viitasalo and Mäkinen 1980).

The relative area occupied by the FT cells in the total fibre area was also calculated (paper IV). This corrected FT% (CFT%) is determined using the FT% and FT:ST area ratio values (see Viitasalo et al. 1980).

5. RESULTS

The most important results are presented below. For more details the original papers (I-V) should be consulted.

5.1. Running technique at different speeds

5.1.1. Stride length, stride rate and running velocity

The increases (p<0.05-0.001) in running velocity, SL and SR (Figure 6, paper III) from submaximal speed 1 to supramaximal speed were observed and their values at the highest speed were 10.74 $\pm$ 0.37 m x s^{-1}, 2.23 $\pm$ 0.14 m and 4.82 $\pm$ 0.24 Hz for males and 9.62 $\pm$ 0.23 m x s^{-1}, 2.01 $\pm$ 0.08 m and 4.79 $\pm$ 0.29 Hz for females. Supramaximal velocity was 108.4 % for all subjects and SR contributed 6.9 % and SL 1.5 % of the observed increase. As expected, significant (p<0.001) differences existed in running velocity between males and females at all speed except submaximal 1. In SR there were no differences between the sexes, but in SL significant (p< 0.01) differences were also found at all speeds other than submaximal 1.

In supramaximal running (paper I) velocity was 8.5 % (p< 0.001), SL 6.8 % (p<0.001) and SR 1.7 % (ns) greater than in maximal running (Table 3). The increase (4.7 %) in SR between maximal and supramaximal running of the elite male sprinters was significant (p<0.05), but there was no change in SL. In the posteffect run of the same group SR was 3.8 % greater (p<0.05) than in maximal running.
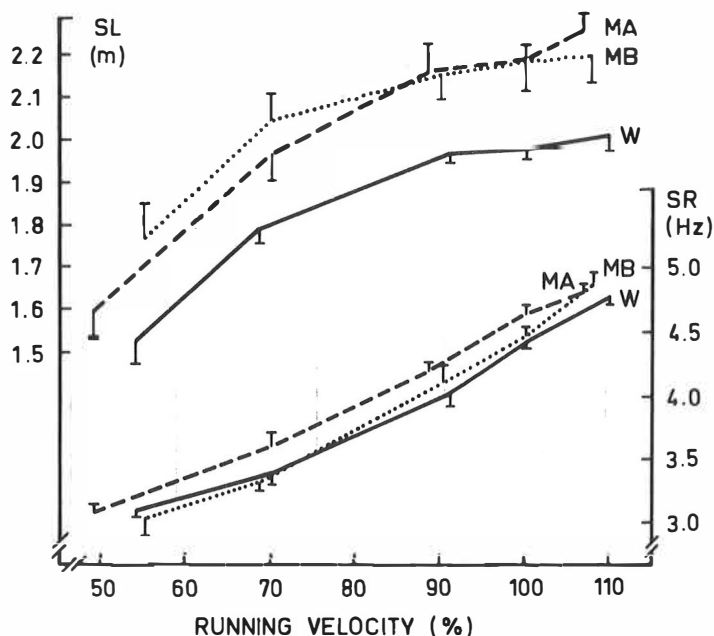
FIGURE 6. Mean (+ SE) values for SL and SR in groups MA, MB and W at different running speeds. Increases in SL were significant (p<0.05-0.001) up to submaximal speed 3 and in SR all increases except for group MA at the highest speed were significant (p<0.05-0.001)

Supramaximal speeds were 10.28 ± 0.48 m x s^{-1} (104.3 $\pm$ 2.5 %; run I) and 10.27 ± 0.35 m x s^{-1} (104.6 $\pm$ 3.4 %; run II) with towing horizontally and vertically simultaneously (paper V). SR was unchanged but SL increased clearly (p< 0.01). No changes were observed in SR or SL in post-effect running compared to maximal run.

A significant correlation (r = .63, p<0.01) was noted between the relative increases in running velocity and stride rate when comparing maximal and supramaximal runs (Figure 7, paper III).
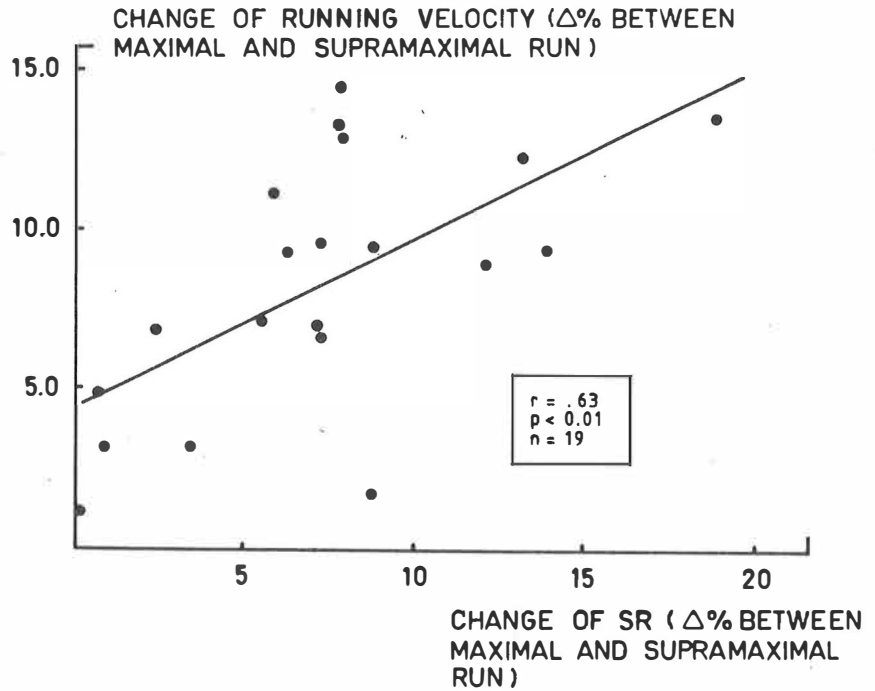
FIGURE 7. Relationship between the relative changes in running velocity and SR for all subjects between the maximal and supramaximal run (y = 4.40 + 0.54x)

5.1.2. Other technique variables at maximal and supramaximal speed

Table 3 presents the other average values of running technique variables in maximal and supramaximal running (paper I). The flight phase was of longer duration (p<0.05) and the contact phase of shorter duration (p<0.001) in supramaximal as compared to maximal velocity. Also during supramaximal running the inclination of the ground shank at the beginning of the braking phase was less vertical i.e. more braking (87 ± 3 vs 89 ± 3 degrees, p<0.05) and the angle of the ground knee at the beginning of the contact phase was greater (p<0.05). Similarly the maximal horizontal velocity

TABLE 3. Mean values of variables of maximal and supramaximal
running velocities for all subjects (n=22)

	Maximal running (M ± SD)	Supramaximal running (M ± SD)	Significance of difference
Running velocity (%)	100.0+0.0	108.5+5.0	
Running velocity (m x s^{-1})	9.25+0.56	10.04+0.49	p<0.001
Stride rate (Hz)	4.49+0.12	4.56+0.16	ns (p<0.10)
Stride length (m)	2.06+0.12	2.20+0.11	p<0.001
Flight phase			
Duration (s)	0.121+0.006	0.125+0.006	p<0.05
Vertical velocity of the shank before (0.01 s) contact (m x s^{-1})	2.00+0.35	1.81+0.38	ns
Braking phase			
Duration (s)	0.043+0.008	0.037+0.012	ns
Inclination of ground shank at beginning of braking phase (deg)	89+3	87+3	p<0.05
Horizontal distance between first contact point and C.G. at beginning of braking phase (m)	0.24+0.04	0.26+0.04	ns
Descent of C.G. (m)	0.01+0.01	0.01+0.01	ns
Deceleration of horizontal velocity			
Absolute (m x s^{-1})	0.33+0.12	0.28+0.10	ns
Relative (%)	3.6+1.4	2.8+0.1	ns
Angle of C.G. at beginning of braking phase (deg)[a]	13+2	14+2	ns
Propulsion phase			
Duration (s)	0.059+0.009	0.059+0.012	ns
Angle of C.G. at end of propulsionphase (deg)[a]	19+2	19+2	ns
Total contact phase			
Duration (s)	0.102+0.004	0.096+0.004	p<0.001
Angle of the ground ankle			
At the beginning (deg)	111+3	113+4	ns
Minimum (deg)	93+5	95+4	ns
Angle of the ground knee			
At the beginning (deg)	153+6	157+5	p<0.05
Minimum (deg)	146+5	147+4	ns
Angle of the ground hip			
At the beginning (deg)	144+6	145+8	ns
Maximal horizontal velocity of the swinging thigh (m x s^{-1})	12.27+0.79	13.44+0.72	p<0.001
Vertical peak-to-peak oscillation of C.G. (m)	0.05+0.01	0.05+0.01	ns

a = angle of C.G. has been calculated between the vertical line and the line
from C.G. to the contact point

of the swinging thigh during contact was faster (p<0.001) in
the supramaximal run.

5.2. Segmental contribution to horizontal velocity of centre of gravity during contact at different running speeds

5.2.1. Segmental contributions

Differences in horizontal velocity of C.G. during the phase
of maximal horizontal deceleration and acceleration between
the male and the female group were significant (p<0.05-0.001)
but in vertical velocity there were no significant differ-
ences (paper II). A comparison between running speeds (sub-
maximal 90 %, maximal 100 %, supramaximal 110 %, maximal
posteffect 100 %) indicated significant differences (p<0.001)
in horizontal direction but not in vertical direction.
Analysis of variance revealed also that all the segmental
horizontal velocities in the phase of maximal deceleration
and acceleration were significantly different in the between-
speed comparison. The level of significance was higher (p<
0.001) for all the subjects than for the male or female
group alone (p<0.05-0.001). In vertical segmental veloci-
ties there were no significant differences. Deceleration of
horizontal velocity of C.G. during the braking phase ranged
from 2.8 % (supramaximal run) to 4.9 % (submaximal run) with
all the subjects in the between-speed comparison (p<0.001).
Also all the differences in the male and female groups were
significant in relative values but not in every case in
absolute values.

The relative segmental contribution to the horizontal
running velocity of both contact phases was the same at dif-
ferent running speeds and for the male and female subjects.

TABLE 4. Segmental horizontal velocities and segmental contribution to velocity of C.G. in the phases of maximal deceleration and acceleration in maximal run (mean $\pm$ SD)

Variable	Maximal deceleration		Segmental contribution (%)		Maximal acceleration		Segmental contribution (%)	
	Men	Women	Men	Women	Men	Women	Men	Women
Duration of maximal deceleration and acceleration from touchdown (s)	0.021 $\pm$ 0.014	0.025 $\pm$ 0.017			0.070 $\pm$ 0.017	0.074 $\pm$ 0.019		
Velocity of C.G. (m x s^{-1})	9.42 $\pm$ 0.49^{xxx}	8.56 $\pm$ 0.41			9.66 $\pm$ 0.57^{xxx}	8.69 $\pm$ 0.38		
Segmental velocities (m x s^{-1})								
Swinging upper arm	7.38 $\pm$ 0.68	6.79 $\pm$ 0.66	2.1	2.1	8.53 $\pm$ 0.68^{xxx}	7.56 $\pm$ 0.28	2.4	2.3
Contact upper arm	11.57 $\pm$ 0.89^{x}	10.73 $\pm$ 0.80	3.3	3.4	11.49 $\pm$ 0.97^{x}	10.54 $\pm$ 0.69	3.2	3.3
Swinging forearm	5.04 $\pm$ 0.79	4.32 $\pm$ 1.00	0.9	0.8	6.76 $\pm$ 0.90^{xx}	5.64 $\pm$ 0.37	1.1	1.0
Contact forearm	14.16 $\pm$ 0.97^{xxx}	12.31 $\pm$ 0.94	2.4	2.3	11.75 $\pm$ 1.24	10.96 $\pm$ 1.20	2.0	2.0
Trunk	9.39 $\pm$ 0.60^{x}	8.71 $\pm$ 0.50	50.9	52.0	10.08 $\pm$ 0.75^{xx}	9.02 $\pm$ 0.47	53.3	53.0
Swinging thigh	12.38 $\pm$ 0.58^{xxx}	10.90 $\pm$ 0.90	12.7	12.4	11.78 $\pm$ 0.97^{x}	10.72 $\pm$ 0.99	11.8	12.0
Contact thigh	7.55 $\pm$ 0.50^{xxx}	6.45 $\pm$ 0.40	7.8	7.3	7.18 $\pm$ 0.55^{xx}	6.28 $\pm$ 0.59	7.2	7.0
Swinging shank	14.36 $\pm$ 0.68^{xxx}	12.75 $\pm$ 0.65	6.9	6.7	13.19 $\pm$ 0.67^{xxx}	12.02 $\pm$ 0.51	6.1	6.2
Contact shank	3.40 $\pm$ 0.56^{x}	2.80 $\pm$ 0.44	1.6	1.5	3.34 $\pm$ 0.81	3.15 $\pm$ 0.88	1.1	1.6
Other segments			11.4	11.5			11.3	11.4

^{x} $p < 0.05$ ^{xx} $p < 0.01$ ^{xxx} $p < 0.001$

The range of segmental contribution of the different speeds, including both sexes, was as follows: swinging upper arm (2.1-2.4 %), swinging forearm (0.8-1.2 %), contact upper arm (3.1-3.4 %), contact forearm (1.8-2.4 %), trunk (50.9-53.7 %), swinging thigh (11.5-13.4 %), swinging shank (6.0-6.9 %), contact thigh (7.0-8.1 %), contact shank (1.1-2.0 %) and other segments (10.9-11.7 %). The relative segmental contribution in maximal run is presented in Table 4.

Horizontal impulses in the braking phase were positive for the swinging thigh but negative for the arms, trunk, swinging shank, contact thigh and contact shank in all the measured velocities. The mean impulse value of the swinging thigh of all the runs was 38 Ns and the respective values of the other segments ranged from -3 Ns (arms) to -42 Ns (trunk). In the propulsion phase the horizontal impulses were positive for other segments except for the swinging thigh and arms which produced negative impulses.

5.2.2. Timing pattern

There was a significant ($p<0.05$) difference in the timing (time from the beginning of contact phase) of the minimal velocity of the swinging shank, which was shorter (0.052 $\pm$ 0.010 s) in men than in women (0.063 $\pm$ 0.007 s) in maximal running. The relative timing of the maximal segmental velocities during contact at different speeds are presented in Figure 8. The only significant difference ($p<0.05$) was in the relative timing of the contact thigh between the supra-maximal and posteffect run for both sexes.
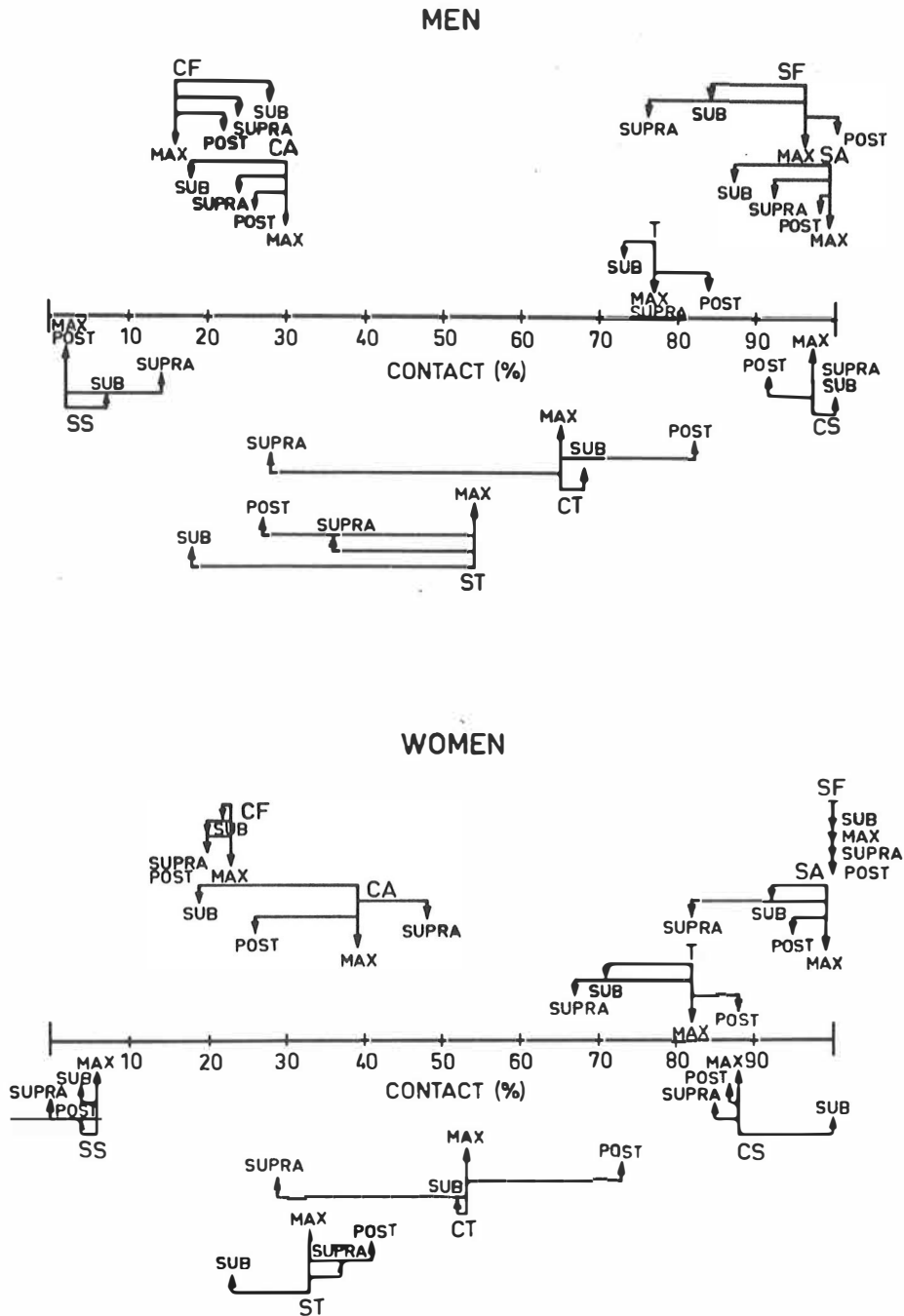
FIGURE 8. Relative timing of the maximal segmental velocities during contact at different running speeds of men and women (SA = swinging upper arm, CA = contact upper arm, SF = swinging forearm, CF = contact forearm, T = trunk, ST = swinging thigh, CT = contact thigh, SS = swinging shank, CS = contact shank)

5.3. Electromyographic activity at different running speeds

5.3.1. Electromyographic activity with increasing speed

The relative values of IEMG (mean of VL and GA) have been calculated from the value of the braking phase at maximal speed and they are presented in Figure 9 (paper III). In the propulsion phase IEMG was markedly lower (p<0.001) than in the braking phase at every speed. At submaximal speed 1 the relative value of male subjects in the braking phase was 53 ± 3 % and that of the females 54 ± 3 %. When running velocity increased, IEMG increased as well; this was particularly marked between submaximal speed 3 and maximal speed (p<0.001). At the highest speed (supramaximal), group MB had very high IEMG activity in the braking phase, and its value of 118 ± 3 % was significantly (p<0.001) greater than for the maximal speed.

In the propulsion phase IEMG also increased with increasing velocity. The lowest value (at submaximal speed 1) was 20 ± 3 % for men and 22 ± 3 % for women. At supramaximal speed the values were 50 ± 5 % and 62 ± 8 % for men and women, respectively. The increase in the EMG value of the female subjects was significant (p<0.05) when running velocity increased from maximal to supramaximal.
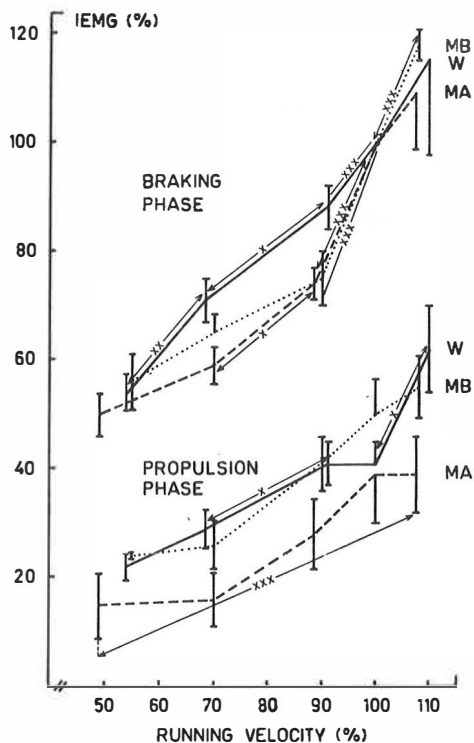
FIGURE 9. Mean (+ SE) relative values for IEMG (mean of VL
and GA) in the braking and propulsion phases for
groups MA, MB and W at different running speeds.
The relative values have been calculated from the
value in the braking phase at maximal speed for
each group (x = p<0.05, xx = p<0.01, xxx = p<
0.001)

5.3.2. General activity pattern during stride

An example of raw EMGs of the monitored muscles during stride
at maximal speed is shown in Figure 10 (paper IV). Figure 11
shows the IEMG activity pattern of leg muscles GA, VL, BF,
GM and RF at maximal and supramaximal speed. Peak activity
at these speeds and at all other speeds occurred during
ipsilateral contact for these muscles except RF, which showed
peak activity during contralateral contact.

MAXIMAL SPRINT RUNNING
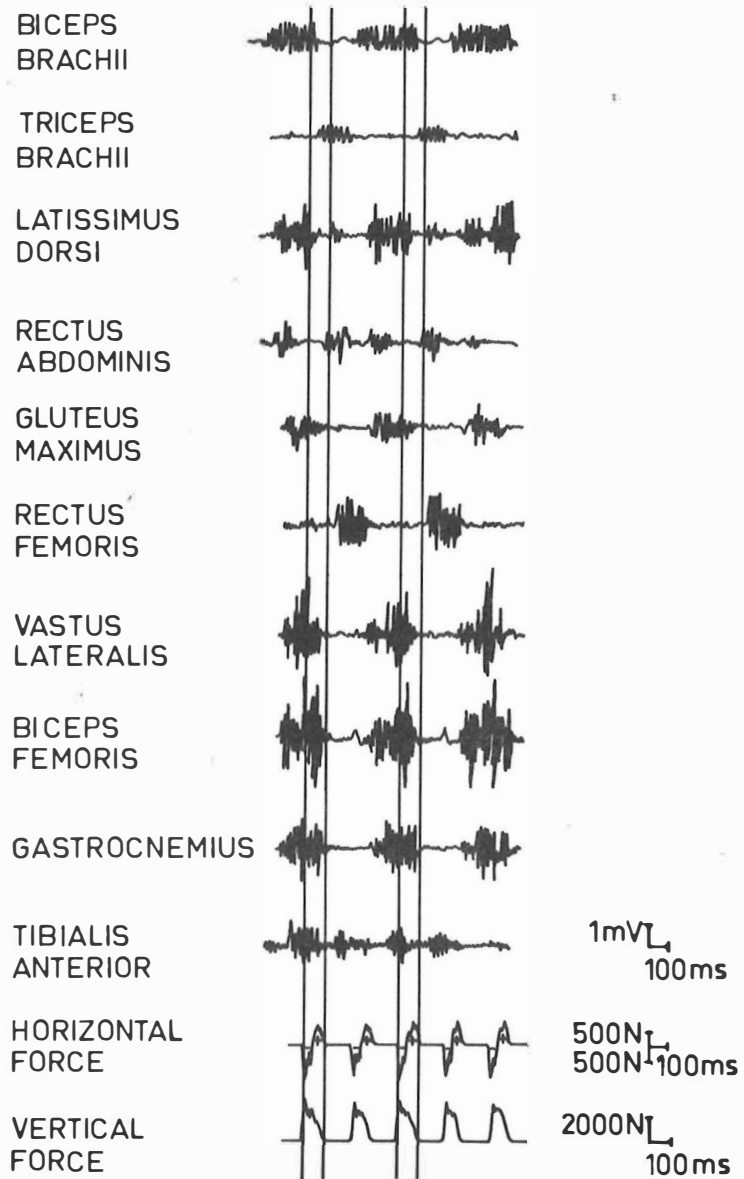
FIGURE 10. An example of raw EMGs of the measured muscles during stride at maximal speed of one subject, shown together with the ground reaction forces
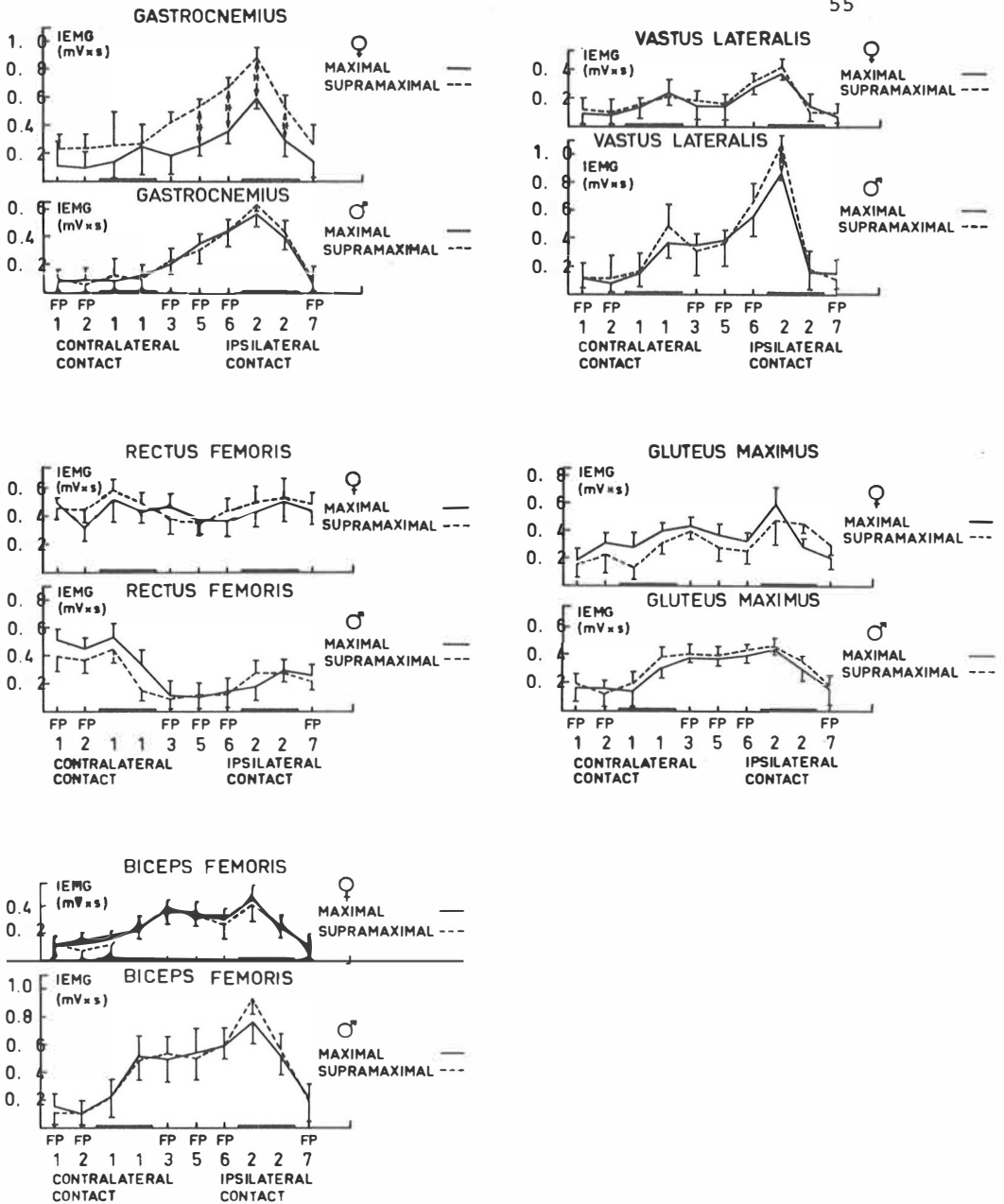
FIGURE 11. Mean (+ SE) values for the IEMG activity of the
five leg muscles during stride at maximal and
supramaximal speed of men and women (FP = flight
phase, x = p<0.05)

5.3.3. Preactivity

Preactivity (PRA) in the phase of FP_6 (Figure 12) increased
significantly (p<0.001) when running speed increased from
submaximal speed 1 to supramaximal speed (paper IV). Figure
12 shows also the relationship between PRA of the five leg
muscles and the average resultant force in the braking phase.
Correlation coefficients (r = .96-.97) between the variables
were statistically significant (p<0.01), both in men and in
women. When PRA-activities were expressed in relative values
no significant differences between speeds or sexes were
observed. The range of PRA-values relative to maximum con-
tact IEMG was from 50 % to 70 %.

5.3.4. Electromyographic activity during contact

Integrated EMG activity of the five leg muscles during con-
tact increased significantly (p<0.001) in each group when
running velocity increased from submaximal speed 1 to maxi-
mal speed (paper IV). The activity of each muscle at maximal
and supramaximal speed during contact can be seen in Figure
11. In the case of female subjects there was significantly
(p<0.05) smaller IEMG activity of GA in the maximal as
compared to the supramaximal run in ipsilateral contact.
In the male subjects the VL muscle demonstrated greater (p<
0.05) ipsilateral braking phase activation at supramaximal
as compared to maximal speed.
    A significant correlation coefficient (r = .64, p<0.05)
was found between the relative changes in stride rate and
IEMG in the braking phase of the male subjects (Figure 13,
paper III).
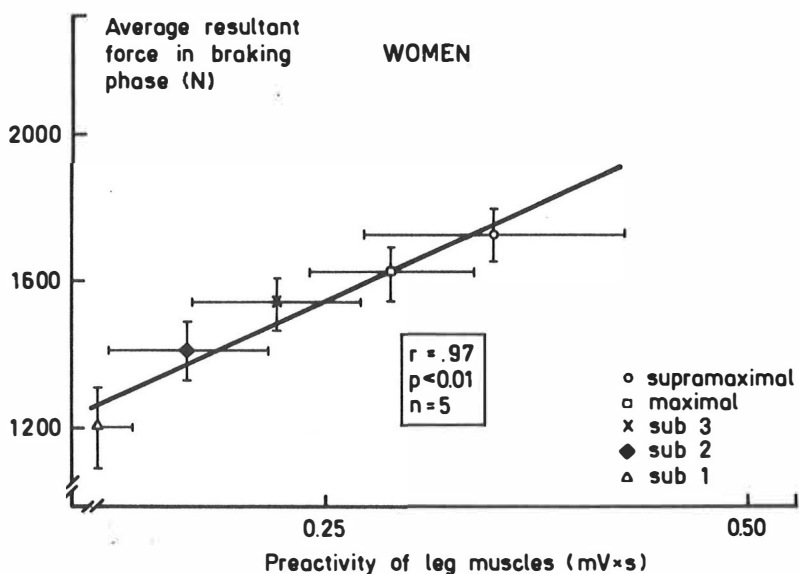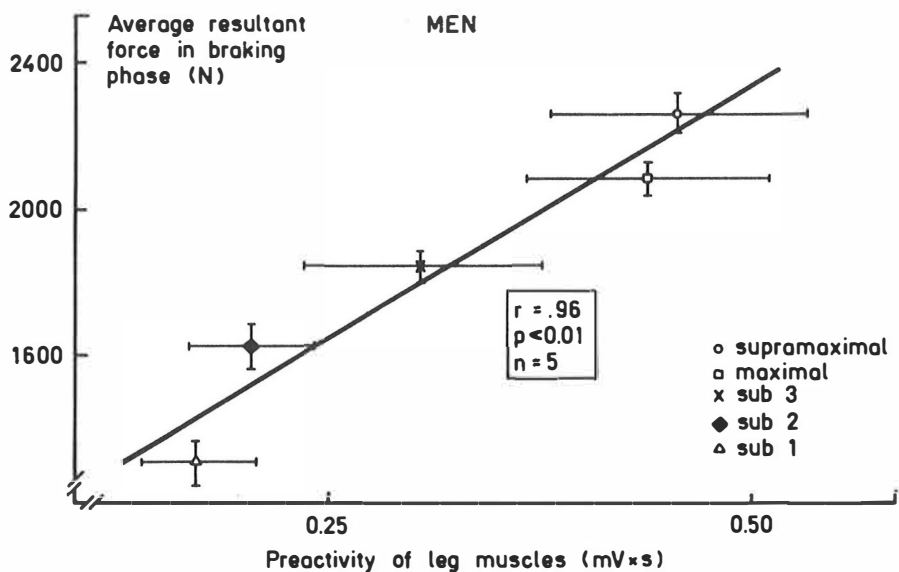
FIGURE 12. Relationship between the average resultant force
in the braking phase and the preactivity of the
five leg muscles at different running speeds of
men and women (mean ± SE; y = 954 + 2750x for
men, y = 1025 + 2100x̄ for women)
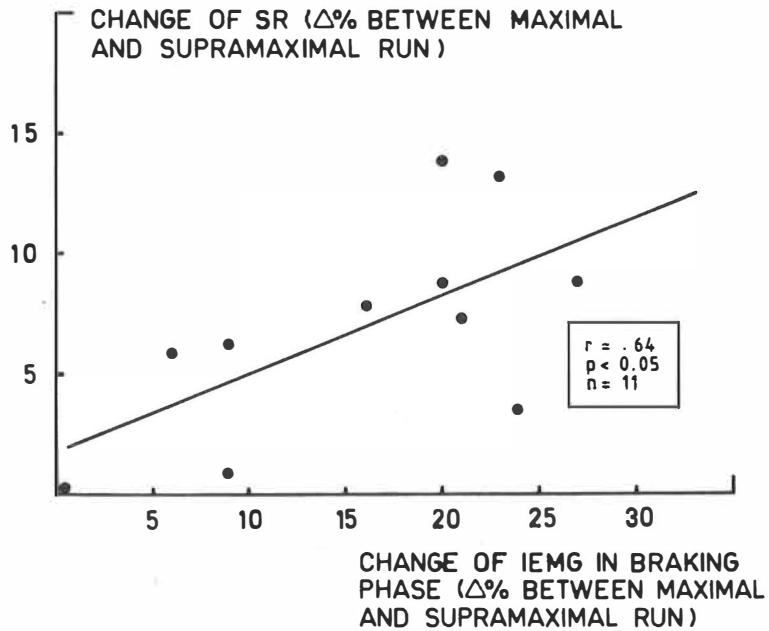
FIGURE 13. Relationship between the relative changes in SR
         and IEMG (mean of VL and GA in braking phase)
         for male subjects between the maximal and the
         supramaximal run (y = 1.78 + 0.32x)

5.3.5. Postactivity

Postactivity (POA) of the five leg muscles (Figure 14) in-
creased significantly ($p < 0.001$) when running speed increased
to maximum but decreased nonsignificantly at supramaximal
speed (paper IV). The correlation coefficient between POA and
the average resultant force in the propulsion phase was sig-
nificant in men ($r = .89$, $p < 0.05$, Figure 14) but not in women
($r = .50$). In relative POA values group MA had a lower ($p <
0.05$) value at the two lowest speeds than the other two
groups. MA was also the only group in which a significant ($p <
0.05$) change (increase) was observed in POA between sub-
maximal 9.0 ± 3.1 % and supramaximal 23.6 ± 4.2 % running.
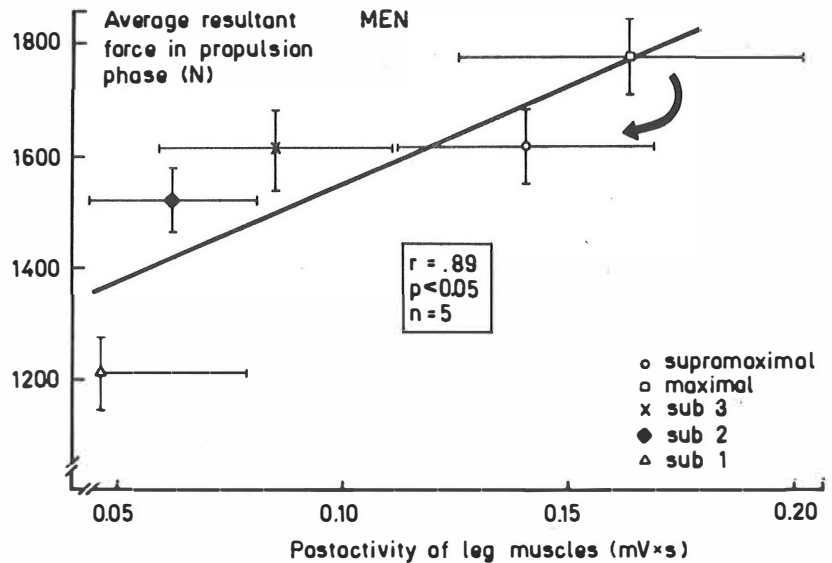
FIGURE 14. Relationship between the average resultant force in the propulsion phase and the postactivity of the five leg muscles at different running speeds of men (mean ± SE; y = 1199 + 3490x)

5.3.6. Minimum activity

Minimum activity (MINA) of the five leg muscles occurred on average in FP_2 and increased significantly (p<0.001) with running speed up to the maximum (paper IV). There were no differences in the relative MINA of the five leg muscles or other muscles between speeds or sexes. The lowest activity of all the muscles was observed in the biceps brachii muscle at submaximal speed 3.

5.3.7. Electromyographic activity related to change in length of the gastrocnemius muscle during the stride cycle

In order to identify EMG activity during actual eccentric and concentric phases for an individual muscle, the instant
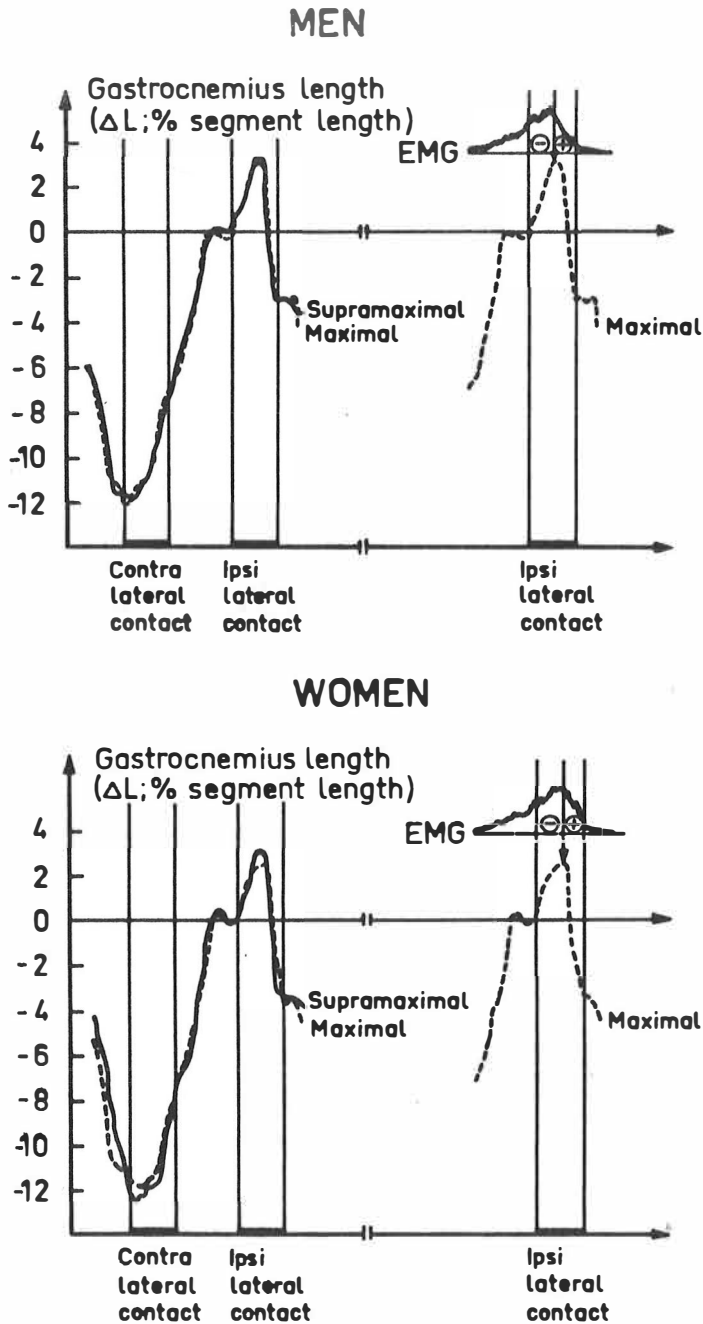
FIGURE 15. Average gastrocnemius length change during stride
at maximal and supramaximal speed for men and
women. Note that the reference length (0 %) is
obtained when the knee and ankle are both at 90
degrees. The right sides of both figures give
examples of typical rectified muscle activity
during maximal running of one male and female
subject. The signs ⊖ and ⊕ refer to the eccentric
and concentric phases, respectively, in the
function of the gastrocnemius muscle

length of the biarticular gastrocnemius muscle at the two
highest speeds is presented in Figure 15 (paper IV). The
curves represent average values for both groups and the
rectified EMG pattern of both figures (men and women)
represents a single but representative case in terms of
timing and amplitude of EMG during maximal sprinting.

5.4. Force production at different running speeds

5.4.1. Ground reaction forces with increasing speed

The values of average resultant force increased in the
braking phase with increased running speed (Figure 16, paper
III). For example, at submaximal speed 1 this force reached
an average value of 1314 $\pm$ 59 N for the males. The respec-
tive value for the females was 1212 $\pm$ 114 N. With the towing
system the resultant forces were 2257 $\pm$ 55 N for males and
1733 $\pm$ 71 N for females. In group MA the increases in force
at the last two test speeds were significant ($p<0.05$), and
in group B the force increase from submaximal speed 3 to
maximal was also significant ($p<0.01$). The differences
between sexes were significant from submaximal speed 2 to
supramaximal speed (submaximal 2; $p<0.05$, submaximal 3 -
supramaximal; $p<0.001$). At maximal and supramaximal speeds
group MA had significantly ($p<0.05$) greater forces than
group MB.

In the propulsion phase the average resultant force in-
creased from the lowest speed to maximal speed in the male
groups ($p<0.01$-0.001) but at supramaximal speed the force
decreased nonsignificantly (Figure 17, paper III). The women
increased the force from submaximal speed 1 to 2 ($p<0.05$),
but thereafter the propulsive resultant force decreased
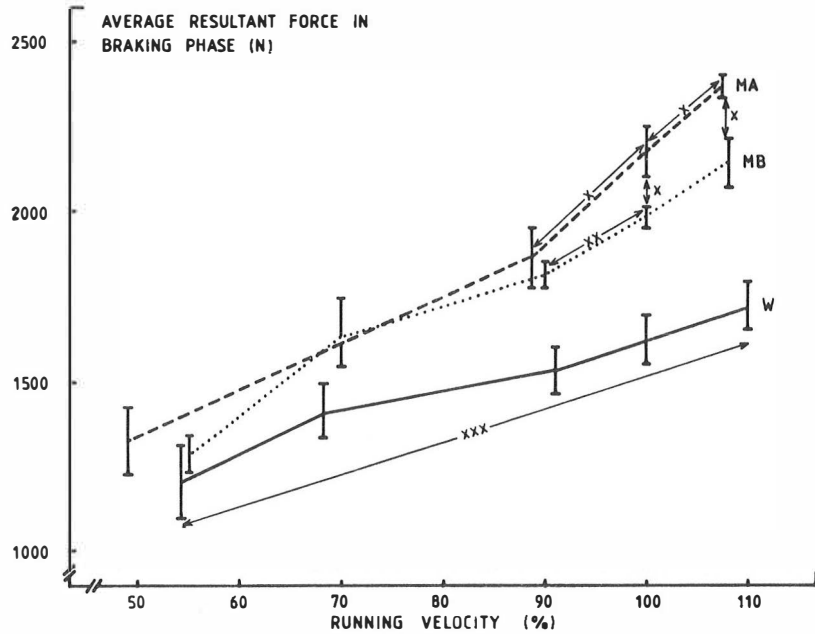
FIGURE 16. Mean (+ SE) values for the average resultant
force in the braking phase for groups MA, MB and
W at different running speeds (x = p<0.05, xx =
p<0.01, xxx = p<0.001)
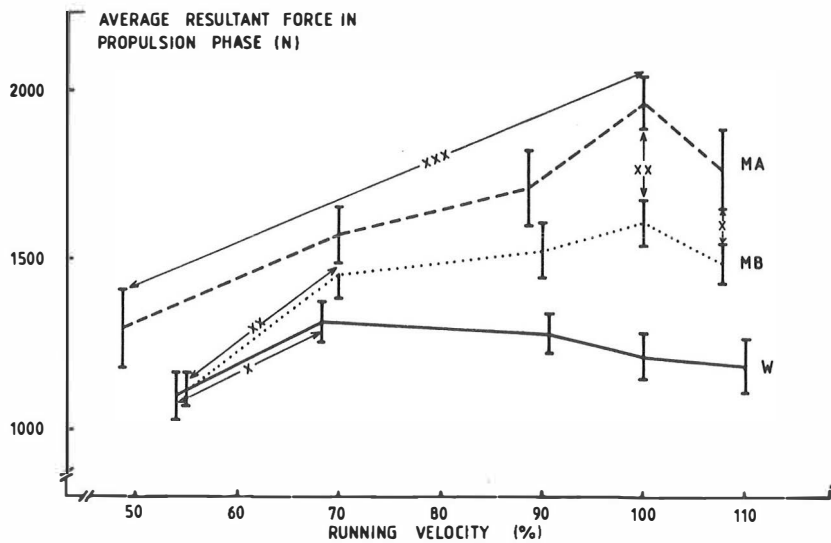
FIGURE 17. Mean (+ SE) values for the average resultant
force in the propulsion phase for groups MA, MB
and W at different running speeds (x = p<0.05,
xx = p<0.01, xxx = p<0.001)

slightly (ns). The lowest force was 1210 ± 70 N for males
and 1100 ± 73 N for females, and the highest values were
1778 ± 76 N (maximal run) and 1320 ± 63 N (submaximal 2),
respectively. The differences between sexes were significant
at all speeds other than submaximal 1 (submaximal 2; $p<0.05$,
submaximal 3; $p<0.01$, maximal and supramaximal; $p<0.001$). In
the propulsion phase group MA had greater forces than group
MB at maximal ($p<0.01$) and supramaximal ($p<0.05$) speeds.

At the two highest speeds there were no differences
between speeds or sexes in the time required to reach maxi-
mal force during contact (paper IV). In the braking phase of
supramaximal running the time to reach maximal horizontal
force lasted 10 ± 6 ms and maximal vertical force 25 ± 10 ms.
The respective values in the propulsion phase were 26 ± 10
ms and 7 ± 8 ms. At submaximal speed 1 the time to reach
maximal force was significantly ($p<0.001$) longer than at
supramaximal speed except for the time to attain maximal
vertical force in the propulsion phase. In the braking phase
the peak horizontal force occurred 79 ± 11 ms and the peak
vertical force 60 ± 8 ms after touchdown and in the propul-
sion phase the values were 45 ± 12 ms and 8 ± 9 ms, respec-
tively.

Table 5 presents detailed horizontal and vertical ground
reaction forces at maximal and supramaximal speed (paper V).
Maximal force and average force in the horizontal direction
during the braking phase were significantly ($p<0.01-0.001$)
greater in supramaximal run I than in the maximal run. The
same variables in supramaximal run I were also greater ($p<0.05$) than in supramaximal run II. In vertical force produc-
tion maximal and average forces were greater ($p<0.05-0.01$)
at supramaximal speed as compared to the other runs. Flight
time was also longer ($p<0.01$) in supramaximal running than
in the other runs.

TABLE 5. Ground reaction forces in various runs (mean $\pm$ SD)

Variable	Maximal run (the third run)	Supramaximal run 1 (the sixth run)	Supramaximal run 2 (the eighth run)	Posteffect run (the ninth run)
Braking phase (ms)	44$\pm$5	46$\pm$5	45$\pm$4	44$\pm$4
Horizontal ground reaction				
Maximal force (N)	880$\pm$147 xxx	1052$\pm$157 x	916$\pm$85	846$\pm$109
Average force (N)	351$\pm$60 xx	428$\pm$68 x	362$\pm$50	349$\pm$37
Vertical ground reaction[a]				
Maximal force (N)	2704$\pm$282 xx	3481$\pm$646	3176$\pm$663 x	2715$\pm$210
Average force (N)	2039$\pm$175 xx	2175$\pm$221	2157$\pm$172 xx	1960$\pm$121
Propulsion phase (ms)	52$\pm$5	49$\pm$7	50$\pm$6	52$\pm$4
Horizontal ground reaction				
Maximal force (N)	595$\pm$76	599$\pm$65	582$\pm$51	585$\pm$67
Average force (N)	360$\pm$42	349$\pm$37	358$\pm$23	371$\pm$45
Vertical ground reaction[a]				
Maximal force (N)	2356$\pm$206	2294$\pm$236	2235$\pm$194	2326$\pm$173
Average force (N)	1286$\pm$61	1203$\pm$126	1195$\pm$74	1263$\pm$105
Total contact time (ms)	96$\pm$7	95$\pm$10	95$\pm$9	96$\pm$8
Flight time (ms)	120$\pm$6 xx	126$\pm$5	127$\pm$6 xx	120$\pm$6

a = body weight is included in vertical forces

5.4.2. Spring constants with increasing speed

The values of spring constants were high in the braking phase and very low in the propulsion phase (Figure 18). In the braking phase the values increased significantly when running velocity increased to maximum but at supramaximal speed they decreased (significantly only in group W; $p < 0.05$). Spring constant values increased most from submaximal speed 3 to maximal speed ($p < 0.001$ for W and $p < 0.05$ for MA). The highest spring constants were in group MA 35.29 $\pm$ 6.64 N x mm^{-1} x kg^{-1}, in group W 24.36 $\pm$ 2.27 N x mm^{-1} x kg^{-1}, and in group MB 14.42 $\pm$ 2.40 N x mm^{-1} x kg^{-1}. The only marked
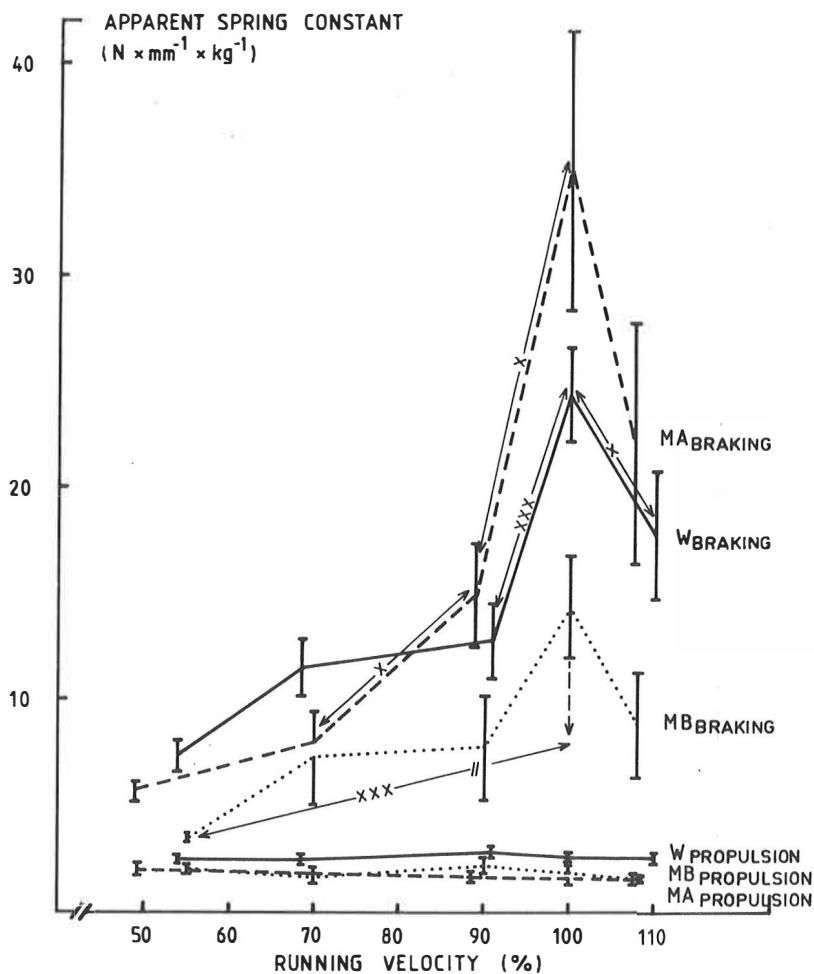
FIGURE 18. Mean (+ SE) values for the apparent spring con-
stant in the braking phase and propulsion phase
for groups MA, MB and W at different running
speeds (x = p<0.05, xxx = p<0.001)

difference (p<0.05) between men and women was at the lowest
running speed, where the women had higher spring constant
values than the men (7.41 $\pm$ 0.73 N x mm^{-1} x kg^{-1} vs. 4.58 $\pm$
0.5 N x mm^{-1} x kg^{-1}). At submaximal 1, maximal and supra-
maximal speeds, group MA had higher values (p<0.05) than
group MB.

No statistically significant changes were observed in
spring constant values during the propulsion phase.

5.4.3. Interrelationships between muscle fibre
        characteristics, ground reaction forces and
        maximal running velocity

Significant correlations were found in male subjects between
the type II percentage of the VL muscle and average net
resultant force (N x kg^{-1}) in the propulsion phase of the
maximal run (r = .53, p<0.05) and maximal running velocity
(r = .76, p<0.01). The corrected type II percentage was sig-
nificantly (p<0.05) greater (64.3 $\pm$ 4.1 %) in group MA than
in group MB (54.0 $\pm$ 7.3 %) (paper IV) and it correlated sig-
nificantly with average net resultant force (N x kg^{-1}) in
the propulsion phase of maximal running (r = .54, p<0.05,
Figure 19) and maximal running velocity (r = .59, p<0.05).
    There were also significant correlations in all subjects
(paper III) between maximal running velocity and force
parameters (average net resultant force in the braking phase,
r = .65, p<0.01; and average net resultant force in the
propulsion phase, r = .84, p<0.001). When force was related
to body weight, a significant correlation (r = .65, p<0.01)
was noted between maximal running velocity and average net
resultant force in the propulsion phase (Figure 20). Stride
length correlated significantly with average net resultant
force in the braking phase (r = .54, p<0.05) and in the
propulsion phase (r = .64, p<0.01) in all subjects during
the maximal run.
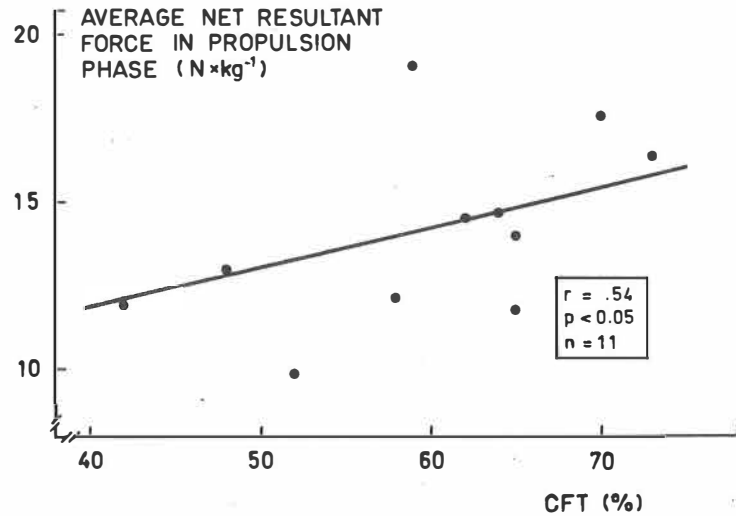
FIGURE 19. Relationship between average net resultant force
(related to body weight) in the propulsion phase
and the corrected type II percentage (CFT%) (y =
4.87 + 0.15x)
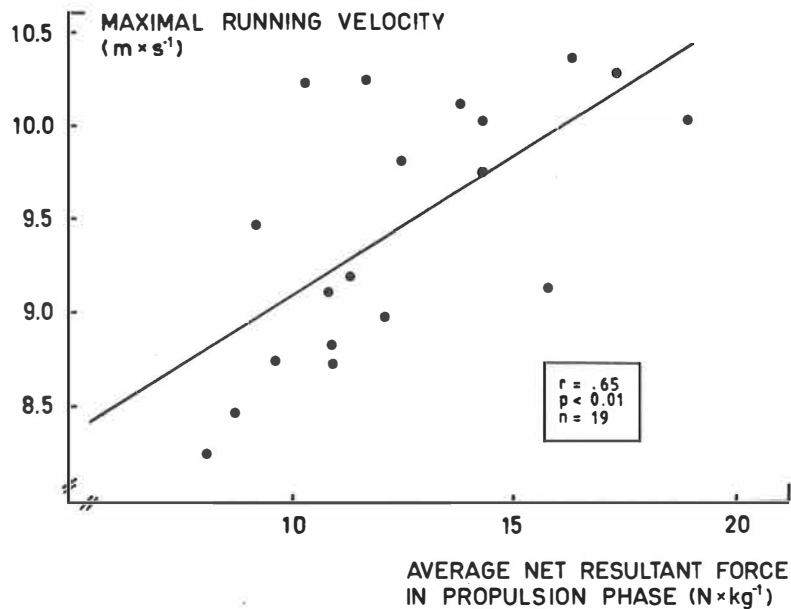
FIGURE 20. Relationship between maximal running velocity and
average net resultant force (related to body
weight) in the propulsion phase for all subjects
during the maximal run (y = 7.61 + 0.148x)

5.5. Anaerobic energy production

5.5.1. Blood lactate

The results of the blood lactate analysis are shown in
Figure 21 (paper V). There were significantly (p<0.05-0.001)
greater values for exercise and recovery (up to the ninth
minute) of the maximal runs as compared to supramaximal ones.
The resting control value was 3.0 ± 0.5 mmol x l^{-1} and the
peak recovery values (10.6 ± 1.2 mmol x l^{-1} for maximal runs
and 8.3 ± 1.4 mmol x l^{-1} for supramaximal runs) were ob-
served for the second minute of recovery.
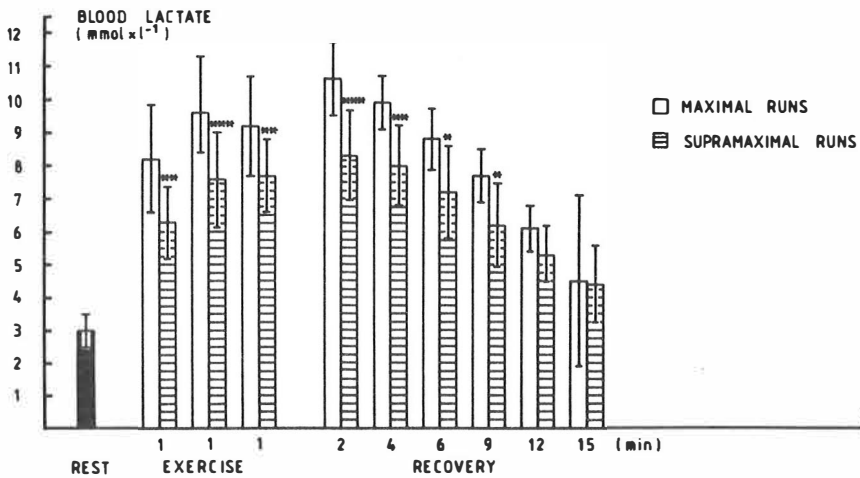
FIGURE 21. Mean ($\pm$ SD) values for blood lactate of the sub-
jects at rest, immediately following exercise and
during a long recovery (x = p<0.05, xx = p<0.01,
xxx = p<0.001)

5.5.2. Oxygen debt

Oxygen debt (net) values during a recovery time of 18 minutes
are presented in Figure 22. Recovery oxygen consumption was
significantly (p<0.05-0.001) higher following maximal runs
than following supramaximal runs in most of the 15-s periods.
During the first 15 seconds oxygen debt was the same for
both runs. Total oxygen debt during 18 minutes was $77.4 \pm$
12.6 ml x kg^{-1} following maximal runs and 59.4 ± 21.6 ml x
kg^{-1} following supramaximal runs (p<0.01).
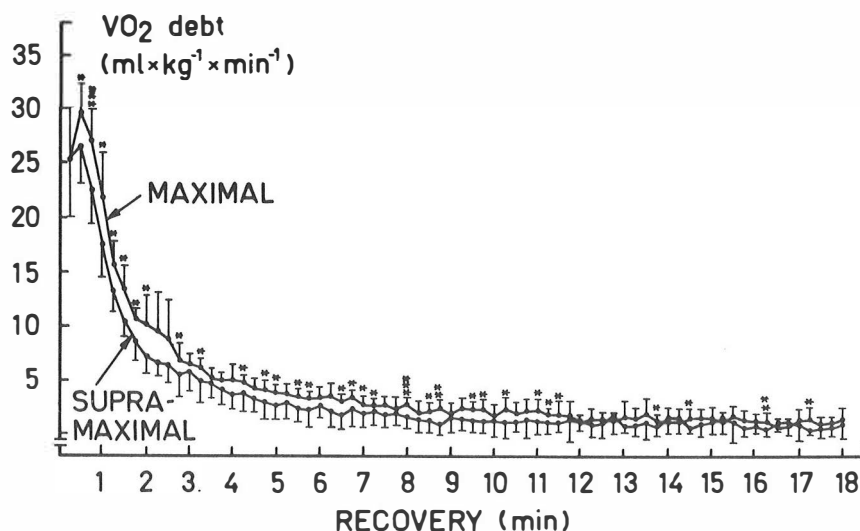
FIGURE 22. Mean (+ SD) values for net oxygen debt of the
subjects following maximal and supramaximal runs
(x = p<0.05, xx = p<0.01, xxx = p<0.001)

6. DISCUSSION

6.1. Primary findings

Electromyographic activity, force and anaerobic energy pro-
duction were studied at different constant speeds among
sprinters. The primary findings of this investigation were
as follows:

(1) Both stride length (SL) and stride rate (SR) increased
    with increasing running speed. As expected the males ran
    faster than the females, and this was primarily due to a
    greater SL in the male sprinters.

(2) In supramaximal running the increase in velocity was
    associated with an increase in either SL or SR.

(3) The relative segmental contribution to the horizontal
    running velocity of both the deceleration phase and the
    acceleration phase during contact was the same at dif-
    ferent running speeds both for the male and the female
    subjects.

(4) Electromyographic activity of the leg muscles increased
    with increasing running speed. It was greater in the
    braking phase than in the propulsion phase at every
    running speed.

(5) The relative change in IEMG during the braking phase of
    the male subjects correlated positively and signifi-
    cantly with the relative change in SR when comparing
    maximal and supramaximal running.

(6) With increasing running speed, there was a corresponding increase in the preactivity of the five leg muscles which correlated significantly with the average resultant force in the braking phase.

(7) Postactivity of the five leg muscles increased significantly up to maximal speed but subsequently decreased non-significantly and correlated positively with the average resultant force in the propulsion phase when running speed increased.

(8) The values of the average resultant force increased in the braking phase with running speed and the differences between sexes were significant. The swinging thigh was the only segment which produced a positive horizontal impulse in the braking phase.

(9) In the propulsion phase, the average resultant force increased significantly from the lowest speed to the maximal speed in the male groups and subsequently decreased nonsignificantly. In the women the force increased significantly only at the lowest two speeds. The differences between sexes were significant at all speeds other than submaximal 1.

(10) Maximal and average forces in the braking phase of supramaximal running were significantly greater than the respective values in maximal running.

(11) Spring constant values were high in the braking phase and very low in the propulsion phase.

(12) Significant positive correlations were noted between muscle fibre characteristics, ground reaction forces and maximal running velocity.

(13) Blood lactate and oxygen debt values for exercise and
     recovery following the maximal runs were significantly
     greater than after the supramaximal runs.

This discussion will concentrate first on running
technique and segmental contribution to running velocity. It
will then examine electromyographic activity, force produc-
tion and, finally, anaerobic energy production.

6.2. Running technique and segmental contribution to running
     velocity

As has been shown earlier (e.g. Luhtanen and Komi 1978),
both SL and SR increased with running speed, but not linear-
ly. SL levelled off, whereas SR increased even at supra-
maximal speed with horizontal towing (Figure 6). An increase
of 8.4 % was observed in supramaximal running velocity, SR
contributing 6.9 % and SL 1.5 %. In test runs with this
towing system the subjects were advised to press the leg as
fast as possible onto the ground to increase SR, and they
obviously succeeded well in doing this. By way of contrast,
in the first study with the same towing system SL increased
6.8 % and SR only 1.7 %. In the latter case the elite male
sprinters succeeded in increasing SR (4.7 %), which may be
due to the fact that they alone had trained in this method
regularly during selected training months. In the former
case all subjects had similar experience in supramaximal
running.
     In addition to the possible influence of the training
per se, the greater increase in SR in the MA group may have
been due to the greater proportion of active fast twitch
muscle volume in the group. Greater active FT muscle mass
has been reported to be related to an increase in stride

rate (Mero et al. 1981). No increase was observed in SR with resultant towing. The angle of draught was from 10 to 17 degrees from the horizontal in the phase of analysis and one can assume that an increase in SL (and flight time) can more easily result when comparing to horizontal towing. Audiograms were transmitted into the ears of a subject during running to stimulate the central nervous system to supramaximal effort. The responses, however, were not seen in the EMG activity of leg muscles or SR. The significant correlation noted between the relative changes in running velocity and SR between maximal and supramaximal (horizontal towing) runs adds further support to the concept that in supramaximal effort it is possible to run at a higher SR than in maximal running.

There can also be other factors, such as motor nerve conduction velocity (NCV), which may be related to the potential increases in SR. NCV has been demonstrated to be faster in athletes trained for speed strength events than in athletes for other events (Lehnert and Weber 1975). It has been suggested that both genetic and environmental factors influence differences in NCV (Kamen et al. 1984). Lastovka (1969) has suggested that training may increase NCV of the posterior tibial nerve. Thus, supramaximal running may have acute and/or long-term training effects on the nervous system. If this is true, then an increased SR combined with greater rate of force production in the braking phase might be used as effective training stimuli.

Edds (1950) and Wedeles (1949) noted an increase in motor nerve axon diameters due to training. Anderson and Edström (1957), on the other hand, noted a decrease, but there are also reports that show no changes in diameters (e.g. Tomanek and Tipton 1967). Since nerve axon diameter is very closely related to conduction velocity (Arbuthnott et al. 1980, Paintal 1973, Waxman 1980), any change in diameter would cause a concomitant change in conduction velocity. Also, histochemical changes in ventral motoneurons following long-term exercise have been observed (Gerchman et al. 1975),

suggesting that dynamic metabolic activity takes place in
motoneurons following chronic exercise. One might therefore
speculate with caution that with supramaximal sprint training
it might be possible to achieve changes in the nervous system,
and therefore to adapt human neuromuscular performance to
the higher level.

Results in technique of maximal running were generally
well in line with earlier studies (e.g. Kunz and Kaufman
1981, Mero et al. 1982, Mann and Herman 1985). When com-
paring maximal and supramaximal running with horizontal
towing the increase in SL was accompanied by a longer flight
phase. However, the end activity of the flight phases did
not differ between the two runs. The vertical velocities of
shank just before contact were 2.00 ± 0.35 m x s^{-1} (maximal)
and 1.81 ± 0.38 m x s^{-1} (supramaximal). If they are related
to the velocity of C.G., the ratios of 0.22 and 0.18,
respectively, can be obtained. If this ratio were higher in
maximal running it would imply that the runners could press
their leg downward relatively faster than in supramaximal
running. For the purpose of increasing primarily SR it might
be attractive to suggest that this ratio should be kept the
same in both running conditions. In supramaximal runs this
would prevent the flight phase (stride) from lengthening and
would cause increases in SR. At touchdown the ground shank
was less erect in the supramaximal run and consequently in a
more braking position. As a result of the braking effect the
horizontal distance between the first contact point and C.G.
increased only slightly (0.02 m, ns), and therefore one
cannot conclusively imply that the active press of the leg
was not fast enough. However, the duration of contact phase
shortened significantly with increasing speed in spite of
the braking effect.

Another kinematic difference between the two runs could
be observed in the knee angle. In supramaximal velocity the
angle of the knee was greater at touchdown: 157 ± 5 degrees
versus 153 ± 6 degrees (maximal). This can be explained
partly by the towing system. The draught was near the centre

of gravity and the hip of the subject went forward with possible effects to straighten the leg. This would then put the leg extensor muscles in a better position to exert forces. At touchdown both the knee and ankle angles decreased (braking phase) first but the hip angle increased during the whole contact at both running speeds. The vertical peak-to-peak oscillation of the C.G., however, was similar to the two runs, and the deceleration of the velocity in the braking phase was slightly less (2.8 % vs 3.6 %) in the supramaximal run. The finding that the relationship of the maximal horizontal velocity of the swinging thigh to the horizontal velocity of C.G. was similar in the two conditions (ratios 1.33 and 1.34, respectively) may also reflect that co-ordinatively the two runs did not differ from each other.

In the whole group of subjects the posteffect run was the same as the "normal" maximal run. However, within the separate groups it was found that the MA group had a significantly ($p < 0.05$) higher SR in the posteffect run and SL had shortened by 0.07 m (ns). Each subject ran twice supramaximally between maximal and posteffect run. These results indicate that it might be possible to obtain acute posteffect benefits from the supramaximal runs, that is, in preparation for competition during warming up.

Despite a clear difference between men and women in maximal running velocity, the relative segmental horizontal contribution to the running velocity was the same at different speeds and for both sexes. In maximal running the phase of maximal deceleration occurred 0.021 ± 0.014 s (23 %) for men and 0.025 ± 0.017 s (27 %) for women after the touchdown. The deceleration phase of the male and female subjects occurred relatively slightly earlier (22 % and 17 %, respectively) in supramaximal running with horizontal towing than in maximal running. Also the deceleration of running velocity was smaller in supramaximal running and these two results emphasize the more economic locomotion at supramaximal speed in the braking phase. The peak of maximal acceleration in maximal run occurred 0.070 ± 0.017 s (75 %)

for men and 0.074 ± 0.019 s (81 %) for women after the touch-
down.

Regarding these findings at maximal speed it was observed
that contribution of the arms to maximal running velocity
was small, and the net horizontal impulses of the arms were
negative (near zero) in both braking and propulsion phases.
The arms act according to the principle of movement and
opposite movement. One arm produces positive and the other
produces negative net impulse and they try to achieve
balance in movement (Mann 1981). In hurdling (Kollath 1983)
the segmental contribution of the arm to vertical velocity
in take-off contact ranged between 1.8-3.0 %, which is very
near to the values for sprinting but it is, however, in a
different direction.

During maximal run the trunk contributed 50.9-53.3 % to
the running velocity for both sexes. The velocity of the
trunk was very near that of C.G. in maximal deceleration but
greater than in maximal acceleration. The same was observed
for the other speeds. The maximal velocity occurred at the
point of 77 % for men and 82 % for women after touchdown.
The segmental contribution of the trunk is the largest of
all the segments because of the mass of that segment. In the
braking phase the net horizontal impulse was negative but in
the propulsion phase it was positive. The parameters of the
trunk (displacement, velocity and force production) are very
close to those of C.G. The contribution of the trunk to the
vertical velocity in hurdling is 36 % (Kollath 1983).

All the velocity curves of both swinging thigh and shank
were above that of C.G. The swinging shank contributed the
largest segmental velocity at the beginning of contact (176 %
and 152 % of the velocity of C.G., for men and women, re-
spectively). The maximal velocity of the swinging thigh
occurred at the point of 54 % for men and 33 % for women
after touchdown. The swinging thigh was the only segment
that produced positive horizontal impulse in the braking
phase. This finding is in agreement with earlier observations
on the contribution of the swinging leg (Luhtanen and Komi

1978, Mero et al. 1986a). However, these earlier studies
have examined the entire leg as one segment. In contrast to
the swinging thigh, the impulse of the swinging shank was
negative in the impact phase but positive in the propulsion
phase. For the development of running technique during the
braking phase it would be advisable to bring the swinging
shank forwards with minor negative impulse to achieve a
higher SR.

The contact thigh and shank had velocities that were all
lower than the running velocity. As in the case of the
swinging leg the contribution of the thigh to running veloci-
ty was greater than that of the shank. The maximal velocity
of the contact thigh and shank occurred at the beginning and
at the end of the propulsion phase, respectively. During
contact the runner tries to produce great forces as fast as
possible. The contact leg has to sustain the impact at the
beginning of the ground phase to get efficient force produc-
tion in the propulsion phase. The time of maximal decelera-
tion was closer to the beginning of contact and also the
vertical oscillation of C.G. was minor in the braking phase
when the running velocity increased. In the same phase the
average negative angular velocity of the ground ankle in-
creased from submaximal to supramaximal speed. The duration
of the braking phase shortened and the changes of the angle
were the same at different speeds for men (19°) and
diminished slightly for women ($20-19-18^O$). This may imply
increased stiffness during the impact phase in the gastro-
cnemius muscle (see Discussion 6.3.) and the muscles are
therefore in a position to utilize elasticity for improvement
of the economy of the progression. Further support for this
hypothesis can be seen in the deceleration of velocity,
which ranged from 4.9 % (submaximal) to 2.8 % (supramaximal)
and which was found to decrease when the running velocity
increased. In supramaximal running the pull helped the sub-
jects to move over the contact point faster, although the
braking distance was somewhat longer than in maximal runs.
In economic running the deceleration of running velocity in

the braking phase should be minimal. If it is not so, the
runner must accelerate very strongly in the propulsion phase,
which leads to very early fatigue.

In the timing pattern of the minimal velocity of the
swinging shank there was a clear difference between men and
women in maximal run and it shows that men had more time to
accelerate the shank at the end of contact. This may also be
partly related to the phase of maximal acceleration, which
occurred somewhat earlier in men than in women. Maximal
velocity was chosen to represent the sensitivity of the co-
ordination. In Figure 8 it can be seen that a comparison of
the runs shows that there were slight differences in
relative timing except the contact thigh. The pattern of the
contact thigh was the same for both sexes. In the maximal
run the contact thigh achieved the maximum during the first
part of the propulsion phase. In the submaximal run the
timing was almost the same but in the other two runs it was
different. In the supramaximal run the maximal velocity of
the contact thigh occurred during the braking phase. One
explanation might be that the deceleration of the running
velocity in the braking phase is the smallest (2.8 %) of all
the runs, which probably enabled the earlier timing for the
contact thigh. The explanation for the late timing of that
segment in the posteffect run is difficult to identify.
However, this timing parameter showed the biggest variation
in the posteffect run and it may also be connected to the
increased braking distance in the supramaximal run. In sprint
training with supramaximal speed the velocities from 101-
103 % seem to be better because stride structure (e.g. a
short braking distance) can be maintained more easily. The
long braking distance is not the only cause of the changed
timing because in the submaximal run there was also a long
braking distance but the timing was very close to that of
the maximal run. Therefore, the smaller deceleration in the
supramaximal run may be a more likely explanation. The
earlier timing can easily be connected to the more efficient
impact phase in the supramaximal run. But as a short-term

effect of the supramaximal run the observed timing pattern
of the contact thigh is not good because it indicates a
longer function during contact. Despite smaller differences
observed between men and women in the timing of maximal
segmental velocities, the basic conclusions can be drawn
that the observed differences are not due to actual sex
differences but that the velocity itself, regardless of
sex, determines the proper technique.

6.3. Electromyographic activity

Preactivity (PRA) of the five leg muscles increased with
running speed (Figure 12) but was relatively the same ranging
from 50 % to 70 %, as compared to the individual ipsilateral
maximum value. Due to the different activity model of each
muscle there were also different PRA curves, as shown in
Figure 11. PRA of the GM muscle in male subjects was
relatively high describing the extension at hip joint which
begins in the late flight phase and continues through con-
tact without any flexion (e.g. Ito et al. 1983), while the
RF muscle had a low preactivity before ipsilateral contact.
The behavior of GM verifies the suggestion made by Ito et al.
(1983) that the beginning of the stretch-shortening cycle of
this muscle, which is a typical one-joint muscle, can be
identified as occurring at the end of the forward swing
phase. For the two-joint muscle, RF, the situation is more
complex. It can be suggested, however, that at the end of
and after ipsilateral contact RF contracts eccentrically due
to extension at the hip joint and flexion at the knee joint.
In the middle of the next flight phase the muscle begins con-
centric contraction when flexing the thigh forwards and it
is not very active in extending the shank before ipsilateral
contact. The role of RF as a hip flexor in running seems

therefore to be more important than as a knee extensor.

Dietz et al. (1979) found that in running the gastro-
cnemius EMG regularly started about 100 ms before ground
contact (velocity of 7.90 m x s^{-1}), which supports the
present results for GA. At the beginning of the contact
great impact forces occur and it is therefore important that
the leg extensor muscles (especially GA, which is close to
the ground), are highly activated and stiff already prior to
and at the moment of impact. It must also be noticed that
the electromechanical delay (the time between the detectable
electric activity (EMG) and effective mechanical response)
of a muscle has been reported to range between 20 and 100 ms
(see e.g. Komi 1984). Thus, the contact on the ground should
take place after this electromechanical delay. One should,
therefore, expect that a high correlation exists between PRA
and early contact forces, as was observed in this investi-
gation. It has been proposed earlier (Melvill Jones and Watt
1971) that preactivation is preprogrammed and dispatched
from higher centres of the nervous system. The results of
Dietz et al. (1981) showed that visual information could
also have an effect on preactivation.

The peak reaction forces took place in the horizontal
direction 10 ± 6 ms and in the vertical direction 25 ± 10 ms
after the first ground contact in supramaximal running.
Since these peak forces exist so soon after the beginning of
the contact the stretch reflex system had most probably not
enough time to become fully activated (Dietz et al. 1979).
For this purpose high preactivation plays a very important
role by increasing stiffness in muscles to resist the early
impact. EMG recordings during falls in humans (Dietz and
Noth 1978a,b, Greenwood and Hopkins 1976) have shown that in
muscles involved in landing, a significant increase in EMG
appears quite shortly after ground contact, corresponding to
a short-latency spinal stretch reflex. In the present ex-
periment peak EMG activity occurred in the braking phase
during ipsilateral contact (except RF). The durations of the
mean braking phases at the two highest speeds were 43-53 ms

and this is in line with the result of Dietz et al. (1979)
that the electrical activity of the GA muscle in running in-
creased sharply 35-45 ms after ground contact. Thus, it can
be suggested that both the high preactivation and the reflex
potentiation after impact may play an important role in
maintaining the high stiffness in the muscle upon and
immediately following impact.

There were no clear differences in the length change of
the GA muscle during stride between maximal and supramaximal
running, not even in contact, despite the different force
production. After contralateral contact the length of GA
began to increase and before ipsilateral contact there was a
small length change due to plantar flexion at the ankle
joint. After touchdown the muscle lengthened and reached its
maximum at the end of the eccentric phase. The length change
during the eccentric phase was about 2.5-3.0 % and it sug-
gests that the muscle is operating through the concept of
the short-range stiffness (Rack and Westbury 1974). It is
produced by the stretched cross-bridges and it has been sug-
gested that short-range stiffness is responsible for the
total stiffness within about 2 % of muscle length (see Hill
1968, Joyce et al. 1969, Ford et al. 1981). It may also be
possible that greater activation of the muscle spindles
during stretching in supramaximal vs maximal running causes
the reflex potentiation to be greater. Increase in EMG ac-
tivity to its maximum at the end of muscle stretch is
likely to increase further muscle stiffness. Moreover,
energy is transferred by the elastic elements from the ec-
centric to the concentric phase and utilization of the
elastic properties has been shown to be important in in-
creasing explosive force production (e.g. Cavagna et al.
1971, Komi and Bosco 1978) and efficiency of movement (e.g.
Thys et al. 1972, Cavagna and Kaneko 1977, Ito et al. 1983,
Komi and Kaneko 1983, Aura and Komi 1986).

Electromyographic activity increased in both contact
phases with running speed (Figure 9). It increased very
clearly at the speeds in the maximal and supramaximal

efforts, when resultant forces were also large in the impact
phase. The significant increase shown by group MB in the
impact phase of the supramaximal run may have been caused by
voluntary recruitment of motor units and reflex activity. In
these "supramaximal" runs the subjects were advised to press
the leg onto the ground as fast as possible, and therefore
it is difficult to determine the balance between voluntary
and reflex contributions to the increased EMG activity.
Schmidtbleicher et al. (1978) and Dietz et al. (1979) have
implied that the electrical activity of gastrocnemius in-
creased sharply after ground contact, and reached its
maximum at the end of muscle stretch and they assumed that
this increase was due to an increased input from the spinal
stretch reflex. In the case of group MB this explanation may
be possible although EMG activity was measured as an average
value of the two leg extensor muscles. The high EMG ac-
tivity would also increase muscle stiffness during impact,
as suggested by Komi (1983) and Gollhofer et al. (1984). On
the other hand, at high supramaximal speeds, inhibition by
structures such as the Golgi tendon organs (GTO) may surpass
the facilitatory "potentiating" effects of the muscle
spindle. In the test runs supramaximal velocities were high,
but the inhibitory role of the GTO cannot be estimated. The
probable increased stiffness of the muscles in the braking
phase can favour the conditions for a good bouncing action
(e.g. Komi 1983). In addition, the use of eccentric contrac-
tions is economical in terms of high mechanical efficiency
(30-180 %; Komi and Kaneko 1983). The values of mechanical
efficiency in the concentric phase of the stretch-shortening
cycle when running at low or moderate speeds have been cal-
culated recently in many studies. Cavagna and Kaneko (1977)
demonstrated that efficiency increases with increasing speed
(1.7-9.2 m x s^{-1}) from 45 % to 70 %. Relatively constant
efficiency values (55 $\pm$ 12.7 %) in a range of speeds (1.9-
6.1 m x s^{-1}) have been presented (Ito et al. 1983). Values
above 20-25 % of normal pure concentric work must result
from the events in the eccentric phase.

In the present investigation performance efficiency can only be evaluated indirectly by force/IEMG ratio (electromyographic activity in the muscle means expenditure of metabolic energy). The ratio (average net resultant force/ IEMG absolute value) decreased in the propulsion phase with increasing running speed and the decrease was also seen in the braking phase, except in male subjects when running velocity increased from submaximal speed 1 to submaximal speed 2. This nonsignificant change may reflect a decreased efficiency during total contact with increasing speed. Recently, in the study by Kaneko et al. (1985), where velocity ranged from 4.0 to 9.5 m x s^{-1}, mechanical efficiency decreased from about 64 % to 17 %. The efficiency of the total performance was higher in the distance runners than in the sprinters at speeds lower than 7 m x s^{-1}, but this relationship tended to reverse at higher velocities showing specificity of training.

The significant correlation between the relative changes of IEMG in the braking phase and SR between the maximal and supramaximal runs suggests that increased neural activation in the supramaximal effort has a positive effect on SR. This could be interpreted as showing that it has some benefits in sprint training by adapting human neuromuscular performance to the higher performance level.

With the exception of RF the peak activity of the leg muscles occurred as expected during the braking phase of ipsilateral contact (Figure 11). Thereafter the IEMG activity began to decrease towards the end of the propulsion phase. These findings are in agreement with earlier studies (Brandell 1973, Elliott and Blanksby 1979b,c, Komi 1983). The study of Komi (1983) also reported that EMG activity in some muscles can decrease to zero before the recorded force had correspondingly become zero during the propulsion phase. Although the vertical ground reaction force curves represent the force of the entire centre of gravity, the result obtained can reflect the efficient use of the stretch-shortening cycle, but it may also indicate the simple time

difference between cessations of EMG activity and mechanical record (see e.g. Bigland-Ritchie et al. 1983).

The activation patterns of the leg extensor muscles during contact in the maximal run were different. At the beginning of contact all muscles (except RF) were very active but the activity of GM and VL decreased quickly during the propulsion phase. During the propulsion phase BF and GA were fairly active and these muscles seem to play a primary role in the propulsion phase of sprint running. The activity patterns of GA and dorsi flexor TA (Figure 10) were very similar to that in the study of Dietz et al. (1979). With the beginning of the subsequent foot extension and still during contact the EMG activity of GA declined. The EMG activity in TA began after ground contact to initiate the subsequent dorsiflexion of the foot during the swing phase. A possible explanation for the simultaneous activity of the muscles just before contact is a general "preactivation" in the TA muscle without any dorsiflexion prior to the contact phase. This is supported by the TA activity during the following braking phase.

The BB muscle of the right arm was activated before and during the braking phase of the right leg. EMG of the TB muscle of the same arm commenced at the end of BB activity and continued for about 100-120 ms. These patterns support the segmental pattern of flexion and extension in the elbow during sprint running. The right latissimus dorsi (LD) is mainly active simultaneously with BB and slightly active during TB activity. The rectus abdominis (RA) of the right side was first activated at the end of ipsilateral contact and then again at the end of contralateral contact. This function is connected to the flexion of the right thigh assisting the flexors in the hip.

In the present experiments postactivity (POA) increased when the average resultant force in the propulsion phase increased (Figure 14), with the exception of supramaximal running. Towing probably helped the subject in pushing the body forwards because both force production and EMG activity

were reduced as compared to maximal running. The relation-
ship between force and POA may show that especially RF but
also BF and GA become more activated with increasing speed
after ipsilateral contact. However, after take-off, when the
heel is moved towards the hip, there is not much EMG ac-
tivity in BF and GA. This flexion of the shank must be caused
by external forces, probably generated as reaction forces
during contact and by the remaining muscle tension due to the
relaxation time of the muscles (Bigland-Ritchie et al. 1983).

Minimum activity (MINA) had the same profile as POA with
changing running speeds. When POA is diminished in supra-
maximal running it is also obvious that MINA is diminished
because of towing. MINA of leg muscles occurred on average
in FP_2 but the individual phase for each muscle was either
FP_2 or contralateral contact concerning all muscles. This
variable of peak relaxation (relative difference between
maximum activity and minimum activity) during stride had
relatively high values at all speeds. The highest relative
values of BB show that in running the upper body can be kept
in a more relaxed state than the leg muscles. However,
absolute MINA of the five leg muscles was small despite the
biarticular muscles representing a more complex function.

6.4. Force production

In the braking phase the resultant force increased relatively
from 63.2 % (submaximal speed 1) to 108.5 % (supramaximal
speed) for men, and the range for women was 74.4-106.4 %,
although the duration of the phase decreased with running
speed (Figure 16). The percentage values are very near those
of the respective relative running speeds. In the propulsion
phase force values were lower than in the braking phase and
decreased nonsignificantly at the highest speed (Figure 17).

However, there were differences between men and women and
between the male subgroups. Significant correlations in the
maximal run were also noted between the average resultant
force and the running variables (velocity and SL). The ob-
served difference of 10.6 % in SL during the maximal run
between men and women is in line with earlier findings (e.g.
Mero et al. 1986b) and it can be explained by the greater
reaction forces of the male subjects. These findings further
emphasize the importance of reaction force production in
running performance. Large vertical force components in the
braking and propulsion phases and a small horizontal force
component in the propulsion phase are typical of force pro-
duction in sprint running. The braking force should be as
small as possible to avoid loss of velocity during the
impact phase. This is partly supported by a positive non-
significant correlation (r = .40) between the average
horizontal force in the braking phase and the relative
deceleration velocity during the braking phase.

The peak values occurred in the braking phase and were
highest in the supramaximal run. The peak vertical force for
male subjects was 4.6 Body Weight (BW) and for female sub-
jects 4.2 BW. Earlier, Payne (1983) reported data from a
single subject showing a peak of approximately 5.5 BW during
sprint running (a rearfoot striker; average velocity of
$9.50 \text{ m} \times \text{s}^{-1}$). Differences in peak values are affected by
contact position. Most sprinters similar to those in the
present study make the first contact high on the ball of the
foot and this tends to cushion out the so-called "heel
spike".

The increase in apparent spring constants of the support
leg during the braking phase was large when running velocity
increased from 90 % to 100 %. The highest value ($35.29 \pm$
$6.64 \text{ N} \times \text{mm}^{-1} \times \text{kg}^{-1}$) was in the elite male sprinters. The
value obtained is higher than those reported earlier for
long jumpers, triple jumpers, less-skilled sprinters (e.g.
Luhtanen and Komi 1980) and marathon runners (Ito et al.
1983). The apparent spring constant is large when the

resultant force at the centre of gravity is large, the peak-
to-peak oscillation and the horizontal displacement of the
centre of gravity are small and the contact time is short.
Using this value, the combined elasticity of muscles,
tendons and bones of the support leg can be evaluated. Group
MA had an elasticity superior to that of group MB. This was
due mainly to the smaller descent of the centre of gravity
during the braking phase, when large resultant forces
compress the leg. The descent 0.010 ± 0.004 m measured in
group MA during the maximal run was smaller ($p < 0.05$) when
compared with 0.018 ± 0.005 m in group MB. At supramaximal
speed elasticity values decreased and a clear difference was
noted also in the descent of the centre of gravity during
impact, which was greater ($p < 0.05$) in all groups with the
towing system. This may imply that the supramaximal running
velocities were too high for the support leg to resist the
impact without falling. As reported earlier (Luhtanen and
Komi 1980, Ito et al. 1983), the spring constant values in
the present data were also low in the propulsion phase and
did not change with running speed.

Significant correlations between type II muscle fibre
characteristics and force production during contact further
emphasize both selection of the athletes for sprint running
and their training status. Also the strong relationship
between type II percentage of the VL muscle (distribution
and corrected) and maximal running velocity is in agreement
with earlier results (e.g. Mero et al. 1981).

6.5. Anaerobic energy production

In each series every run lasted about 5.0-5.5 s and recovery
between runs was five minutes. During one run the energy
yield can be attributed to the splitting of endogenous

energy-rich phosphagens (intramuscular stores of adenosine triphosphate and creatine phosphate). Anaerobic glycolysis can also occur during short supramaximal exercise (over oxidation) and pronounced intramuscular lactate accumulation is observed (Jacobs et al. 1983). In the recovery phase of one run skeletal muscles resynthesize phosphagen at the expense of anaerobic glycolysis (e.g. Embden et al. 1926, Ambrosoli and Cerretelli 1973, Cerretelli et al. 1975) and through oxidation (Harris et al. 1976) and during this recovery accumulated lactate diffuses into the blood. The lactate production (Δlactate) calculated from blood lactate after the first maximal run was 5.2 mmol x 1^{-1}. This rate agrees well with the calculations of about 1 mmol x 1^{-1} x s^{-1} reported for maximal rates (Newsholme 1980). However, the corresponding lactate production after the first supramaximal run was only 3.2 mmol x 1^{-1}. The same significant difference was seen in all lactate responses except in the last two recovery values. This clearly demonstrates a lower utilization of anaerobic chemical energy sources in supramaximal running.

The total net oxygen debt demonstrates a low level of recovery reproduction following work. During 18 min it was 77.4 $\pm$ 12.6 ml x kg^{-1} after maximal runs and was 30.3 % greater than after supramaximal runs. This difference agrees with the peak lactate value, which was 27.7 % higher after maximal runs. Frishberg (1983) has shown that in treadmill running the total net oxygen debt was 36 % lower than in overground condition (100 yd), a difference which also demonstrates a lower energy yield in assisted conditions.

6.6. Conclusions

The conclusions of the present investigation are summarized
as follows:

(1) In supramaximal running with a horizontal towing system
    it is possible to run at a higher SR than in maximal
    running.

    This conclusion is based on the results noted in
    experienced sprinters using a horizontal towing system.
    The data suggest that supramaximal sprinting can be an
    additional stimulus for the neuromuscular system during
    training and also beneficial in preparing for competi-
    tion during warming-up.

(2) Running speeds ranging from 90 % to 110 % can be bene-
    ficial in sprint training because their coordination
    pattern resembles that of the normal maximal run.

    The main result leading to this suggestion was that the
    relative segmental contribution to the horizontal
    running velocity of both the deceleration phase and the
    acceleration phase during contact was the same at dif-
    ferent running speeds for both male and female sub-
    jects. A critical point in stride structure is the
    beginning of the touchdown. Especially in supramaximal
    running the active pressing of the leg down before
    contact is very important and therefore the velocities
    from about 101 % to 103 % seem to be more suitable
    because the coordination pattern can be maintained more
    easily and the contact leg can resist the impact with-
    out falling. This active pressing would prevent the
    flight phase (stride) from lengthening and would cause
    increases in SR. Also the timing pattern of the contact
    leg would closely resemble normal maximal running. The

use of the swinging thigh is very important in running coordination because it is the only segment to produce a positive horizontal impulse in the braking phase.

(3) Preactivity increases stiffness in leg muscles, which is needed to resist high impacts during the very first stages of contact.

This phenomenon was demonstrated by the strong relation-ship observed between preactivity and the average resultant force in the braking phase. Since peak forces exist very soon after the beginning of the contact, the stretch reflex system most probably has insufficient time to become fully activated.

(4) The possible reflex activity and elastic elements cause an enhancement of muscle force during the subsequent propulsion phase.

Peak EMG activity of the leg muscles occurred in the braking phase during ipsilateral contact (except RF), which refers to the reflex potentiation shown by earlier studies. This increase in EMG activity to its maximum at the end of muscle stretch is likely to further increase muscle stiffness. Moreover, energy is transferred by the elastic elements from the eccentric to the concentric work phase. Utilization of the elastic properties has been shown to be important in increasing explosive force production and efficiency of movement in the propulsion phase.

(5) The length change of the GA muscle during the eccentric phase is about 2.5-3.0 %, which suggests that the muscle is operating through the concept of short-range stiffness.

This conclusion is derived from the results obtained during maximal and supramaximal running. The division of the contact according to this method gives more exact information for identifying EMG activities of the GA muscle during actual eccentric and concentric phases. In the case of GA the division was very close to the conventional method of dividing the contact phase by the horizontal force record into braking ("eccentric") and propulsion ("concentric") phases. The short-range stiffness is produced by the stretched cross-bridges and it is responsible for the total stiffness within about 2 % of muscle length, as shown in the literature.

(6) With increasing speed, the efficiency of running may decrease during contact.

This suggestion is based on the ratio of average net resultant force/IEMG absolute value, which during contact decreased slightly (ns) with increasing running velocity. The method employed is indirect, although it will provide new possibilities for evaluating the economy of human locomotion.

(7) Postactivity and minimum activity of the muscle can be used to measure the level of relaxation during running.

Each individual muscle has its own work (contraction) and rest (relaxation) phases during running. In the case of one joint muscles it is very easy to use postactivity and minimum activity as relaxation variables but it is more difficult when investigating multijoint muscles. Theoretically, for example, the rest period of the VL muscle should be long and the increase in EMG activity (e.g. before contact) should be great but short in duration in order to maintain high running economy.

(8) Average net resultant force is strongly related to running velocity during maximal running.

This conclusion is derived from the significant correlations between the average net resultant force and the running variables (velocity and SL). These findings emphasize the importance of reaction force production in running performance; the measurement of these forces during training periods may give valuable information on training-induced effects.

(9) The values for the average net resultant force explain the difference in running velocity between men and women.

In SR the sexes were undifferentiated but the men had a clearly longer SL and the subsequent difference in running velocity can be explained by the greater reaction forces of the male subjects.

(10) Muscle fibre characteristics are related to the selection of talent and the training-induced effects in sprint running.

This suggestion receives support primarily from the significant correlations noted between muscle fibre characteristics and running performance. Because development in maximal running velocity during sprint training is very limited, it is important to discover potential talent (e.g. a high percentage of FT fibres) in the training system. On the other hand, muscle fibre area measurements give additional information on training-induced effects (e.g. strength training vs FT fibre area).

(11) Anaerobic energy production is lower in supramaximal than in maximal running.

The total net oxygen debt and the peak blood lactate value following the supramaximal run demonstrated clearly lower values than after maximal running. These observations give additional support to the notion of lower anaerobic energy production in assisted short efforts. This reduced energy production may have relevance for athletic training in many events.

TIIVISTELMÄ

Tutkimuksessa selvitettiin lihasten sähköistä aktiivisuutta,
voimantuottoa ja anaerobista energiantuottoa pikajuoksussa.
Juoksut (45 m) suoritettiin sisähallissa, ja nopeudet vaihtelivat submaksimaalisesta supramaksimaaliseen. Koehenkilöinä oli mies- (n = 25) ja naispikajuoksijoita (n = 16), ja
monet heistä olivat osallistuneet olympiakisoihin, maailmanmestaruuskisoihin tai euroopanmestaruuskisoihin vuosien 1979
ja 1984 välisenä ajanjaksona. Ensimmäisissä mittauksissa mukana olleet koehenkilöt juoksivat kaksi submaksimaalista,
kaksi maksimaalista, kaksi supramaksimaalista ja lopuksi yhden normaalin maksimaalisen juoksun (ns. jälkivaikutusjuoksun). Juoksunopeudet olivat vaihdellen 90 —110 %. Supramaksimaalinen nopeus saatiin aikaan vaakavedolla, siten että
avustava juoksija veti kuminauhan välityksellä. Toisissa
mittauksissa koehenkilöt juoksivat vähintään kaksi kertaa
viidellä eri nopeudella submaksimaalisesta (52.7 %) supramaksimaaliseen (108.4 %). Viimeksi mainitun nopeuden saamiseksi käytettiin samaa vaakavetosysteemiä kuin ensimmäisellä
kerrallakin. Kolmansissa mittauksissa koehenkilöt juoksivat
kolme sarjaa, joista ensimmäisessä oli kolme maksimaalista,
toisessa kolme supramaksimaalista ja kolmannessa ensin kaksi
supramaksimaalista ja lopuksi kaksi maksimaalista (jälkivaikutus-) juoksua. Nopeudet olivat 98.8 —104.6 %. Elektromekaaninen vetolaite hinasi juoksijaa samanaikaisesti sekä
eteenpäin että hieman (10 —17 astetta vaakatasosta) ylöspäin
(ns. resultanttiveto). Keskimääräinen vedon voima oli 24 —26
newtonia.

Jokainen juoksu filmattiin vakionopeuden vaiheessa
(35 —45 m lähdöstä), jolloin juoksija oli voimalevyanturin
päällä. Toisissa ja kolmansissa mittauksissa rekisteröitiin
myös eri lihasten (n = 10) sähköistä aktiivisuutta (EMG)
tässä vaiheessa. Filmianalyysin avulla selvitettiin juoksun

tekniikkaa, kehonosien vaikutusta juoksunopeuteen, näennäistä jousivakiota ja kaksoiskantalihaksen lihaspituutta. Voimalevyanturin tulostuksesta saatiin juoksuaskeleen voima-aika -arvoja. Lihasten sähköistä aktiivisuutta mitattiin pintaelektrodeilla käyttäen telemetrialaitteistoa. Tukivaiheen ja lentovaiheen lihasaktiivisuudet analysoitiin keskimäärin 50 ms:n jaksoissa. Edellä mainittujen menetelmien toistettavuus vaihteli; korrelaatiokerroin oli 0.70 — 0.98. Kolmannen mittauskerran yhteydessä mitattiin veren laktaattipitoisuutta sormenpäistä otetuista verinäytteistä ja happivelkaa suoritusten jälkeen kerätyistä hengityskaasunäytteistä. Lihasnäytteet otettiin ulommasta reisilihaksesta solujakauman ja solujen keskimääräisen pinta-alan määrittämiseksi.

Päätulokset osoittavat, että sekä askelpituus että askeltiheys lisääntyivät (p<0.05 — 0.001) juoksunopeuden kasvaessa. Miesten ja naisten maksimaalisen juoksunopeuden ero johtui selvästä (p<0.01) askelpituuden erosta. Supramaksimaalisessa juoksussa nopeuden kasvu tapahtui lisäämällä joko askelpituutta tai askeltiheyttä (p<0.05 — 0.001). Askeltiheyden lisäykseen päästiin vain vaakavedon avulla. Juoksun teknisissä yksityiskohdissa oli myös useita selviä eroja maksimaalisen ja supramaksimaalisen juoksun välillä. Jälkivaikutusjuoksussa parhailla miesjuoksijoilla oli suurempi (3.8 %; p<0.05) askeltiheys kuin vaakavedolla suoritettuja juoksuja edeltäneessä maksimaalisessa juoksussa. Kehonosien suhteellinen vaikutus juoksunopeuteen sekä tukivaiheen maksimaalisen hidastuvuuden että kiihtyvyyden vaiheissa oli sama eri juoksunopeuksilla (90 —110 %); sukupuolten välillä ei ollut myöskään eroja. Jalkalihasten sähköinen aktiivisuus lisääntyi (p<0.05 — 0.001) juoksunopeuden kasvaessa, ja se oli suurempi (p<0.001) jarrutusvaiheessa kuin työntövaiheessa. Lihasaktiivisuusmallit askeleen aikana osoittivat, että jalkalihaksista ulomman reisilihaksen, kaksoiskantalihaksen, ison pakaralihaksen ja kaksipäisen reisilihaksen aktiivisuushuiput olivat tukijalassa (ipsilateraalinen tukivaihe). Sen sijaan suoran reisilihaksen aktiivisuushuippu oli jalan heilahdusvaiheessa kontralateraalisen tukivaiheen aikana. Mie-

hillä ulompi reisilihas ja naisilla kaksoiskantalihas olivat selvästi (p<0.05) aktiivisempia supramaksimaalisen juoksun ipsilateraalisessa jarrutusvaiheessa kuin maksimaalisen juoksun vastaavassa vaiheessa. Viiden edellä mainitun jalkalihaksen keskimääräinen esiaktiivisuus lisääntyi ja korreloi positiivisesti (p<0.01) jarrutusvaiheen keskimääräisen resultanttivoiman kanssa juoksunopeuden kasvaessa. Miesjuoksijoiden kaksoiskantalihaksen ja ulomman reisilihaksen lihasaktiivisuuden suhteellinen muutos jarrutusvaiheessa korreloi positiivisesti (p<0.05) askeltiheyden suhteellisen muutoksen kanssa verrattaessa maksimaalista ja supramaksimaalista juoksua. Juoksunopeuden kasvaessa lisääntyivät (p< 0.05 —0.001) keskimääräiset resultanttivoimat molemmissa tukivaiheen osissa (lukuun ottamatta työntövaihetta suurimmilla testinopeuksilla). Miesten ja naisten välillä oli selvät (p<0.001) erot reaktiovoimissa erikoisesti maksimaalisella ja supramaksimaalisella nopeudella. Maksimaaliset ja keskimäärġiset voimat jarrutusvaiheessa olivat vetosysteemeillä suoritetuissa juoksuissa suuremmat (p<0.01 —0.001) kuin normaalissa maksimaalisessa juoksussa. Näennäiset jousivakioarvot olivat suuria jarrutusvaiheessa ja hyvin pieniä työntövaiheessa. Jarrutusvaiheessa ne lisääntyivät selvästi (p< 0.05 —0.001) juoksunopeuden kasvaessa maksimaaliseksi, mutta supramaksimaalisessa juoksussa ne laskivat — tosin merkitsevästi (p<0.05) — vain naisilla. Tilastollisesti merkitseviä (p<0.05 —0.001) positiivisia korrelaatiokertoimia todettiin lihassoluominaisuuksien, tuotettujen reaktiovoimien ja maksimaalisen juoksunopeuden välillä. Veren laktaattipitoisuus ja happivelka olivat suuremmat (p<0.05 —0.001) maksimaalisten kuin supramaksimaalisten juoksujen jälkeen.

Tutkimuksen tulosten mukaan vaakavedolla tapahtuvassa supramaksimaalisessa pikajuoksussa on mahdollista juosta suuremmalla askeltiheydellä kuin normaalissa maksimaalisessa pikajuoksussa. Myös optimaalinen juoksutekniikka, lisääntynyt hermostollinen aktiivisuus ja aktiivisen, nopean lihassolukon massa vaikuttavat positiivisesti askeltiheyden kasvuun. Supramaksimaalinen pikajuoksu on harjoittelussa teho-

kas lisä-ärsyke hermo-lihasjärjestelmälle, ja se voi olla
myös hyödyllinen verryttelyssä valmistauduttaessa kilpailui-
hin. Juoksunopeudet 90:stä 110 %:iin ovat koordinaatio-omi-
naisuuksiltaan hyvin lähellä normaalia maksimaalista juoksua
ja siten tehokkaita pikajuoksuharjoittelussa. Kriittinen
kohta askelrakenteessa on tukivaiheen alku, ja varsinkin
supramaksimaalisessa pikajuoksussa on kiinnitettävä erityis-
tä huomiota aktiiviseen jalan alas painamiseen, jolloin es-
tetään jarrutusvaiheen pidentyminen. Tämän perusteella näyt-
tää siltä, että pienet ylinopeudet (n. 101 — 103 %) ovat so-
pivampia, koska koordinaatiomalli on helpompi säilyttää.
Heilahtavan reiden käyttö korostuu pikajuoksussa jarrutus-
vaiheen aikana, koska se on ainoa kehonosa, joka tuolloin
tuottaa positiivista voimaimpulssia vaakasuuntaan.

Esiaktiivisuus lisää jalkalihaksissa jäykkyyttä
(stiffness), jota tarvitaan vastustettaessa suuria törmäys-
voimia tukivaiheen alussa. Tämä on tärkeää, koska mahdolli-
nen venytysrefleksisysteemi ei ehdi aktivoitua heti tör-
mäyksen alussa ja toisaalta jokaisella lihaksella on oma
elektromekaaninen viiveensä. Lihaksen elastiset osat tehos-
tavat voimantuottoa jarrutusvaihetta seuraavassa työntövai-
heessa yhdessä mahdollisen venytysrefleksisysteemin kanssa.
Kaksoiskantalihaksen pituuden muutokset jarrutusvaiheen ai-
kana viittaavat siihen, että lihas toimii "lyhytaikaisen
jäykkyyden" -periaatteella (short-range stiffness). Pituuden
muutoksen avulla tehty tukivaiheen jako eksentriseen ja kon-
sentriseen osaan on hyvin lähellä muita jaottelussa käytet-
tyjä menetelmiä, mutta omalta osaltaan mahdollistaa lihas-
aktiivisuuden tarkan mittauksen mainituissa vaiheissa. Li-
haksen sähköisen aktiivisuuden rekisteröinnillä voidaan ar-
vioida suorituksen rentoutta ja taloudellisuutta.

Keskimääräinen nettoresultanttivoima tukivaiheen aikana
vaikuttaa ensisijaisesti askelpituuteen ja sitä kautta juok-
sunopeuteen. Miesten ja naisten väliset erot juoksunopeudes-
sa johtuvat askelpituuden eroista, jotka selittyvät miesten
suuremmasta reaktiovoimantuotosta. Supramaksimaalinen pika-
juoksu on myös tehokas nopeusvoimaharjoite jalkojen ojenta-

jalihaksille. Tämä perustuu juoksun aikana kehittyviin suu-
riin reaktiovoima-arvoihin, ja menetelmää voidaankin käyttää
monien urheilulajien voimaharjoittelussa. Lihassoluominai-
suudet vaikuttavat voimantuottoon juoksuaskeleen aikana ja
siten koko juoksusuoritukseen. Sekä solujakauma- että pinta-
alamäärityksiä tulisikin tehdä valittaessa lahjakkuuksia
juoksuharjoitteluun ja seurattaessa harjoitusvaikutuksia.
Anaerobinen energiantuotto on pienempi supramaksimaalisessa
kuin normaalissa maksimaalisessa pikajuoksussa. Tämä havain-
to antaa lisätukea aikaisemmille johtopäätöksille, että an-
aerobisen energiantuoton osuus on pienentynyt kevennetyissä
lyhytaikaisissa suorituksissa. Mainitulla tiedolla on luon-
nollisesti käyttöä monien urheilulajien harjoittelussa.

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