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Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance-trained athletes and sprinters

K. Häkkinen and K. L. Keskinen

Department of Biology of Physical Activity, University of Jyväskylä, 40100 Jyväskylä, Finland

Summary. Seven male elite strength-trained athletes (SA) from different weight categories, six elite sprinters (SPA) and seven elite endurance-trained athletes (EA) volunteered as subjects for examination of their muscle cross-sectional area (CSA), maximal voluntary isometric force, force-time and relaxation-time characteristics of the leg extensor muscles. The SA group demonstrated slightly greater CSA and maximal absolute strength than the SPA group, while the EA group demonstrated the smallest values both in CSA and especially in maximal strength ($p < 0.05$). When the maximal forces were related to CSA of the muscles, the mean value for the SA group of $60.8 \pm 10.0\ \mathrm{N \cdot cm^{-2}}$ remained slightly greater than that recorded in the SPA group $55.0 \pm 3.1\ \mathrm{N \cdot cm^{-2}}$ and significantly greater ($p < 0.05$) than that recorded in the EA group $49.3 \pm 4.0\ \mathrm{N \cdot cm^{-2}}$. The mean value in the SPA was also significantly greater ($p < 0.05$) than that of the EA group. The isometric force-time curves differed between the groups ($p < 0.05$-0.01) so that the times taken to produce the same absolute force were the shortest in the SPA group and the longest in the EA group. With force expressed as a percentage of the maximum, the force-time curves showed that the SPA group demonstrated still shorter times to a given value ($p < 0.05$), especially at the lower force levels, than the other two groups. With regard to the differences in force production per CSA and in the shape of the force-time curves, the present findings may be explained by possible differences both in the rate and the amount of neural activation of the muscles and/or in the qualitative characteristics of the muscle tissue itself. The present findings characterize the very specific nature of high resistance strength-, sprint- and endurance-training stimuli over a very prolonged period of time.

Key words: Muscle cross-sectional area — Muscle strength — Force-time curve

Introduction

When a skeletal muscle is subjected to prolonged high resistance strength-training, it adapts by becoming larger and stronger. Maximal voluntary strength is quite well related to the cross-sectional area (CSA) of the muscle (Ikai and Fukunaga 1968; Maughan et al. 1983; Schantz et al. 1983; Ryushi et al. 1988).

An interesting question arises as to whether the muscle tissue would always have the same force production per unit of mass or CSA, or would it be possible that a muscle could become stronger without necessarily increasing its CSA. It has been demonstrated that increases in maximal strength during strength-training with very heavy loads may in part also be a result of the increased neural activation of the trained muscles, not only in previously untrained subjects (Moritani and DeVries 1979; Häkkinen and Komi 1983) but also in strength-trained athletes (SA) (Häkkinen et al. 1985a). In fact, some recent experiments have reported that elite SA, with a long and intensive high resistance strength-training background of several years, were able to produce greater maximal force per CSA than normal untrained males (Ryushi et al. 1988; Häkkinen 1989).

Effects of sprint- and/or jumping-training, during which low loads but high contraction velocities are utilized, differ specifically from those of high resistance strength-training. Sprint- and/or

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Offprint requests to: K. Häkkinen

jumping-training has an influence primarily on rapid neural activation of the trained muscles leading to increased development of explosive strength (Häkkinen et al. 1985b). However, the changes in maximal strength as well as muscular hypertrophy during this type of training usually take place to a lesser degree than those caused by high resistance strength-training (Komi 1986; Häkkinen 1986).

Endurance-training involves a physical loading that differs completely both from high resistance strength-training as well as from sprint-training. Endurance-training is characterized by a high overall volume of exercise performed against low resistances but with a long duration. This type of training leads to physiological adaptations in energy production through oxidative metabolism without observable changes in muscle mass and/or strength (Gollnick 1981). In fact, prolonged endurance training may even interfere with maximal strength and/or development of explosive strength (Hickson 1980; Hunter et al. 1987).

The purpose of the present study was to examine muscle CSA and the characteristics of force production in elite strength-trained athletes, sprinters and endurance-trained athletes who had very different and highly specialized training backgrounds for several years.

Subjects and methods

Subjects. Seven male SA, six male sprinters (SPA) and seven elite endurance-trained athletes (EA) volunteered as subjects for the study. The physical characteristics of the groups are presented in Table 1. The SA were elite competitive powerlifters (from several weight categories from 67.5 to 100.0 kg) who had been strength-training for 5–10 years. Their strength-training was characterized by very heavy loads up to their maximum but only a few repetitions were performed in each set of exercises. The SPA were elite competitive sprinters and jumpers in track and field events who had been training specifically for explosive strength and speed for 5–10 years. Their typical strength-training sessions consisted primarily of exercises of an explosive nature in which low loads but high and/or maximal contraction velocities were used. The EA were elite competitive swimmers with an endurance-type of training for swimming (excluding maximal strength-training of the leg extensor muscles) over 5–10 years. Almost all of the athletes in these three different groups were medalists in their event in the Finnish championships.

Table 1. Physical characteristics of the groups of subject (SA = strength-trained athletes; SPA = sprinters; EA = endurance-trained athletes)

Variable		SA ($n=7$)	SPA ($n=6$)	EA ($n=7$)	Significance of differences
Age	Mean	28.0	24.7	21.0	SA/EA**
(years)	SD	± 4.7	±3.9	±3.1	
Height	Mean	170.6	184.1	183.7	SA/SPA**, SA/EA**
(cm)	SD	± 6.8	±6.4	±5.4	
Mass	Mean	83.3	78.8	77.3	
(kg)	SD	±11.9	±6.5	±4.4	
Body fat	Mean	16.1	9.9	12.9	SA/SPA**, SA/EA**
(%)	SD	± 3.9	±1.7	±1.9	SPA/EA*

* = $p<0.05$
** = $p<0.01$

Testing. The subjects were carefully familiarized with the testing procedures of voluntary force production during several warm-up contractions preceding the actual maximal contractions. Bilateral isometric leg extension force-time curves, maximal forces, maximal rates of force development and relaxation-time curves were measured on an electromechanical dynamometer (Komi 1973). The knee and hip angles were 107° and 110°, respectively. The subjects were carefully instructed to respond to an auditory signal by exerting maximal force as rapidly as possible, and to maintain that force as long as the signal was audible (2.5 s). They were also told to relax their muscles as fast as possible when the signal ceased. From 3–6 maximal contractions were usually recorded from each subject until maximal force was obtained. The force was recorded on magnetic tape (Racal Store 7) and analysed with a HP 1000 F computer system.

Maximal force was defined as the highest value of force recorded during the entire contraction. In the force-time curves, the times taken to increase the force from a level of 100 N to 500, 1000, 2000, and 2500 N (absolute scale) and from 10% to 30%, 60%, and 90% of the maximum (relative scale) were calculated (Häkkinen et al. 1980). The maximal rate of force development ($N \cdot s^{-1}$) was also calculated (Viitasalo et al. 1980). In the relaxation phase of the contraction the time needed to reduce the force to 10% was calculated.

The CSA of quadriceps femoris (QF) of the right thigh was measured with an ultrasonic apparatus (Aloka Fansonic, SSD-190). The CSA was measured at the midpoint between the greater throchanter and the lateral condyle. The CSA of QF was then calculated from the picture obtained from the computerized system within the apparatus (Ryushi et al. 1988).

The measurements of the thigh girth were made with a tape measure applied around the relaxed muscles with the subject in a sitting position. The proximal, medial and distal portions of the thigh were measured and averaged for further analyses.

The percentage of body fat was estimated from the measurement of skinfold thickness (Durnin and Rahaman 1967).

Standard statistical methods were used for the calculation of means, standard deviations, standard errors and coefficient of correlation. Differences between the values of the subject groups were tested for significance by Student's *t*-test. Values are given as mean ± SD in the text and as mean ± SE in the figures.

Results

The average value of the thigh girth in SA was greater than that recorded for SPA ($p<0.01$) and EA ($p<0.001$) (Fig. 1). The average values in the CSA of QF in SA, SPA and EA were 80.4 ± 10.0, 80.1 ± 6.8 and 72.8 ± 7.8 cm^2, respectively, but the

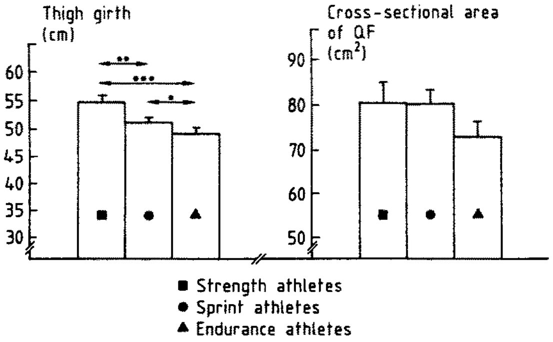

Fig. 1. Mean (±SE) thigh girth and mean (±SE) cross-sectional area of the quadriceps femoris (QF) muscle ($* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$)

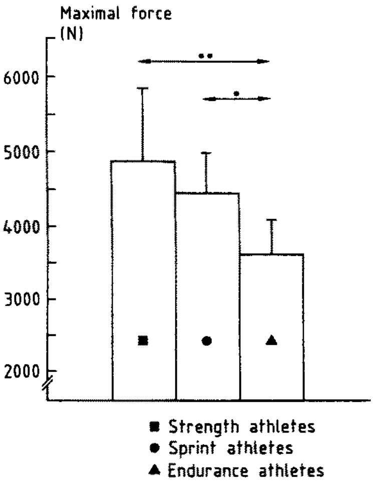

Fig. 2. Mean (±SE) maximal voluntary isometric leg extension force ($* = p < 0.05$, $** = p < 0.01$)

differences between the groups were not statistically significant (Fig. 1).

The maximal voluntary isometric leg extension force of 4860±982 N in SA was slightly greater (NS) than that of 4416±538 N in SPA and significantly greater ($p < 0.05$) than that of 3592±456 N recorded for EA (Fig. 2).

In the whole sample of subjects the individual values in the CSA of QF muscle correlated significantly ($r = 0.70$, $p < 0.001$) with the individual values of maximal voluntary force (Fig. 3).

When the maximal force values were related to the CSA of QF muscle, the difference among the groups became smaller. The mean value of 60.8±10.0 N·cm^{-2} in SA was only slightly greater than that of 55.0±3.1 N·cm^{-2} for SPA but significantly greater ($p < 0.05$) than that of 49.3±4.0 N·cm^{-2} recorded for EA (Fig. 4). The difference in these values between SPA and EA was also statistically significant ($p < 0.05$).

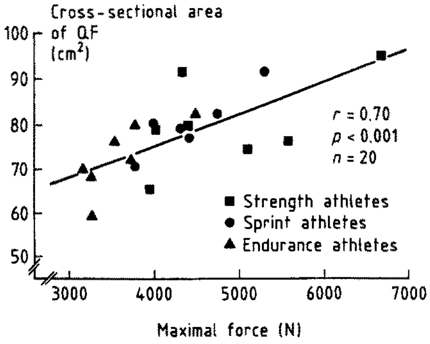

Fig. 3. The relationship between the cross-sectional area of the quadriceps femoris muscle and maximal voluntary isometric leg extension force

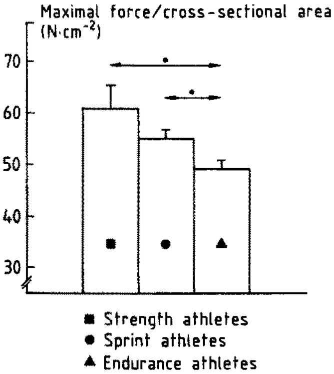

Fig. 4. Mean (±SE) maximal voluntary isometric leg extension force per cross-sectional area of the quadriceps femoris muscle ($* = p < 0.05$)

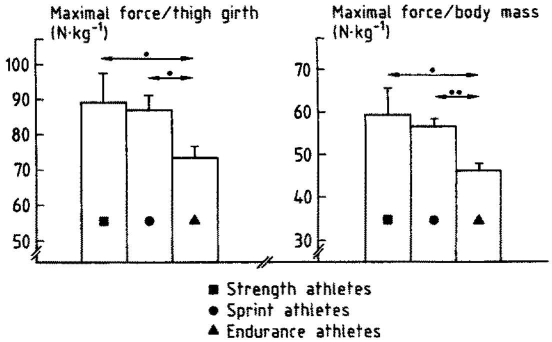

Fig. 5. Mean (±SE) maximal voluntary isometric leg extension force related to thigh girth and to body mass ($* = p < 0.05$, $** = p < 0.01$)

When the maximal force values were related to the thigh girth, both SA and SPA demonstrated greater values ($p < 0.05$) than EA (Fig. 5). This was also true for the force values related to the body mass (Fig. 5).

The shapes of the isometric force-time curves in absolute values differed between the groups so

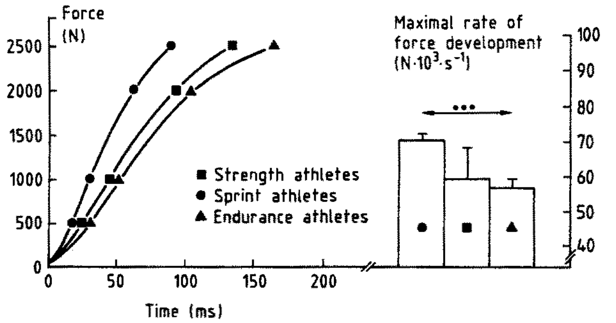

Fig. 6. Average force-time curves of the leg extensor muscles calculated for absolute values (up to a force level of 2500 N) and mean (±SE) maximal rate of force development in the explosively produced maximal voluntary isometric contraction (*** $=p<0.001$)

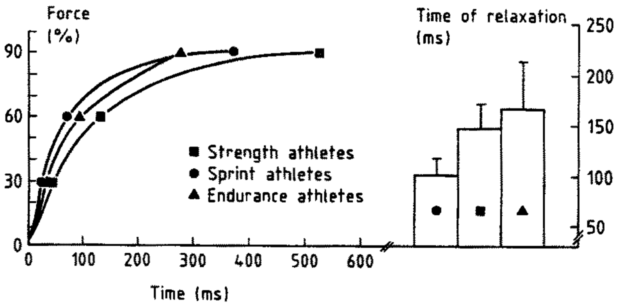

Fig. 7. Average force-time curves of the leg extensor muscles calculated as a percentage of the maximum force developed (up to 90% of the maximum) and mean (±SE) time of relaxation in the explosively produced maximal voluntary isometric contraction in the subject groups

that the times to produce the same absolute force levels in SPA were significantly shorter than in SA ($p<0.05$) and EA ($p<0.01$) (Fig. 6). The average times of force production between SA and EA were not statistically significant. The maximal rate of force development was accordingly greater in SPA than in SA (NS) and EA ($p<0.05$) (Fig. 6).

When the isometric force in the force-time curves was calculated as a percentage of the maximum developed, the times to produce force levels of 30% and 60% of the maximum in SPA were shorter than in EA ($p<0.05$) and SA ($p<0.01$) (Fig. 7). The average times to produce these relative forces did not differ significantly between EA and SA. The time to produce relative forces of 90% of the maximum was longer ($p<0.01$) in SA than in EA. No statistically significant differences were observed in the times of relaxation among the groups (Fig. 7).

Discussion

The present SA demonstrated slightly greater CSA and maximal absolute strength than SPA, while EA demonstrated the smallest values both in the CSA and especially in maximal strength. The times of force production were shorter in SPA than in the other two groups, while no differences between the groups were observed in the time of relaxation. However, it was most interesting to observe that when the maximal forces were related to CSA of the muscle, SA demonstrated slightly greater values than SPA and both of these groups had significantly greater values than EA.

Initial increases in strength during the earlier weeks of strength-training, especially among previously untrained subjects, are accounted for largely by neural adaptations with a gradually increasing contribution from muscle hypertrophy, when the training extends over several months or years (Sale 1986; Komi 1986; Häkkinen 1986). The increase in CSA of the muscle is primarily due to the enlargements of individual muscle fibres of both types, although it may be slightly greater in fast twitch than in slow twitch fibres (MacDougall 1986; Komi 1986; Häkkinen 1986).

However, the specific type of strength-training may be of importance with regard to the magnitude of neural adaptations and especially muscle hypertrophy. Sprint and/or explosive type low-resistance strength-training with a short duration of contraction leads usually to a smaller amount of muscular hypertrophy and to smaller maximal strength development than those caused by the typical high-resistance strength-training used by SA such as weightlifters and powerlifters (Häkkinen 1986). They use primarily very heavy loads up to their maximum but perform only a few (such as 1-5) repetitions in each set of exercises. The ultimate degree of muscle hypertrophy may be produced by the strength-training adopted by bodybuilders. In their training each muscle group is repeatedly exercised by slightly lower loads but with several (such as 6-12) contractions until concentric failure with only a short recovery before the next set of exercises of a similar type. This type of strength-training may not necessarily lead to the increases in maximal strength that would directly correspond to the gains in muscle mass (Häkkinen 1986).

The present findings demonstrated that SA possessed slightly greater CSA as well as maximal absolute force of the QF muscle than the SPA group and, as could be expected, also EA. For the whole sample of subjects, the correlation coefficient between the CSA and maximal force of the muscle was quite high. However, when the maximal force values were related to CSA of the muscles, SA still demonstrated slightly greater values than SPA and significantly greater values than EA. In SA the interindividual variations in the force values per CSA were rather large so that the difference between SA and SPA was not statistically significant. It is possible that these larger interindividual variations in SA could be related to possible variations in the individual high resistance strength-training programmes. The training of the present SPA group included strength-training of normal but especially explosive type but the training loads in the various exercises were generally smaller than those utilized by the SA group. The present findings, therefore, indicate that maximal force per CSA can be influenced especially by high-resistance low repetition strength-training lasting for several years (Ikai and Fukunaga 1970; Ryushi et al. 1988; Häkkinen 1989). Whether this change results from training-induced adaptations in the neuromuscular system, primarily from increased neural input to the trained muscles leading to greater force output, or from changes in the muscle tissue itself, is difficult to distinguish (Ryushi et al. 1988; Häkkinen 1989). Other factors such as the differences in the fibre composition of the muscles may be involved as well (Maughan et al. 1983; Komi 1984).

The training programme of EA consisted mostly of a considerable amount of daily swimming of increasing distances excluding the maximal strength training for the leg extensor muscles. Maximal force per CSA in EA was not only much smaller than in SA but it was also maller than in SPA (Maughan et al. 1983). In fact, the average value of $49.3 \pm 4.0\ \mathrm{N \cdot cm^{-2}}$ in EA was even slightly smaller than that of $52.4 \pm 5.2\ \mathrm{N \cdot cm^{-2}}$ recorded recently for untrained adult males under similar test conditions (Häkkinen 1989). These observations indicate that typical endurance-training which is characterized by a high overall volume of exercise performed against low resistances but with a long duration may not only interfere with development of strength (Hickson 1980) but it may even lead to decreased maximal force production per unit of CSA of the muscle. The present results support the concept of the specificity of training and further characterize the specific influences of different training stimuli on the neuromuscular system during a very prolonged period of time. However, some caution should be exercised with regard to these interpretations, because there are some limitations in the present analysis, in which the force may not exactly represent the correct contribution of the individual muscle groups involved (Ryushi et al. 1988; Häkkinen 1989).

In normal human movement and especially in several athletic activities, the time taken to produce a force level is often even more important than the absolute force level. This is true especially in sprinting and jumping. The shape of the isometric force-time curve is influenced by the amount and rate of neural activation (Komi 1986; Häkkinen 1986), muscle fibre composition (Viitasalo and Komi 1978) and state of training of an individual (Häkkinen et al. 1985a, b). Explosive type strength-training which utilizes lower loads but high contraction velocities may have a specific influence on rapid neural activation of the muscles and correspondingly on rapid force production as indicated by the shape of the force-time curve (Häkkinen 1986). Typical high resistance strength-training which utilizes high training loads with slow contraction velocities tends to lead to improvements primarily in maximal strength and the higher force portions of the force-time curve (Häkkinen 1986). Prolonged endurance-training which utilizes typical aerobic exercises in which low loads are repeated with slow contraction velocities may even lead to the lengthening in the times of force production (Viitasalo and Komi 1978).

When the force-time curves were analysed in absolute values, the times to produce the same absolute forces were the shortest in SPA, while EA demonstrated the longest time for force production. The maximal rate of force development was accordingly the greatest in SPA and the smallest in EA. These specific shifts in the shape of the force-time curves are, therefore, well in line with the concept of the specificity of prolonged training. When the force-time curves were compared with respect to the percentage of the maximum force developed, the differences in the shape of the curves between the groups naturally became smaller, but SPA still demonstrated the shortest times of force production, especially at the lower forces. The observation that the time to produce the high relative forces was the longest in SA may be related to their high absolute forces and their high resistance-training background as well as to the specific nature of their sports event of powerlifting (Häkkinen et al. 1984). The differences among the present groups in relaxation characteristics of the neuromuscular system were slight, although the times of relaxation tended to be the shortest in SPA and longest in EA.

In summary, the primary findings with the present elite athletes showed that especially SA and also SPA produced greater values than EA not only in maximal absolute force but also in maximal force per CSA of the muscle. The times of force production were the shortest in SPA and the longest in EA. The present findings may be explained by possible differences both in the rate and amount of the neural activation to the muscles and/or in the qualitative characteristics of the muscle tissue itself due to highly specific high resistance strength-, sprint- and endurance-training stimuli over a very prolonged period of time.

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