Eur J Appl Physiol (1988) 57:39—44

European Journal of Applied Physiology and Occupational Physiology

Force of knee extensor and flexor muscles and cross-sectional area determined by nuclear magnetic resonance imaging

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Summary. The maximal strengths of knee extensor (E) and flexor (F) muscles were compared in a group of 6 male subjects aged 24—31 years.

Cross-sectional area (CSA) of E and F was evaluated from planimetric measurements of Nuclear Magnetic Resonance (NMR) imaging axial scans, carried out at five levels along the thigh. Maximal CSA for E was found at 2/3 upper femur height and at 1/3 lower femur height for F.

Maximum isometric force (MIF) of E was found to be 135% greater than that of F. The maximum CSA of E was found to be 93% larger than CSA of F.

The calculated mechanical advantage of the flexors was estimated to be 13.8% higher than that of the knee extensors (0.116 ± 0.012 and 0.132 ± 0.005, respectively). However, when MIF of E and F were standardised for their respective CSA, no significant difference was found between their stress: $80.1 \pm 15.5\ N \cdot cm^{-2}$ for E and $70.5 \pm 7.0\ N \cdot cm^{-2}$ for F.

From the present study, it is concluded that no significant difference exists between the maximum stress of knee extensor and flexor muscles despite large differences in their absolute values of force and CSA and that the NMR imaging technique enables accurate in-vivo determination of the CSA of individual muscles.

Key words: Isometric force — Nuclear magnetic resonance — Cross-sectional Area

Introduction

The maximum strength of a muscle is known to be closely related to its Cross-Sectional Area (CSA) (Fick 1910; Weber 1846). This relationship has been described in vitro for animal muscles (Barany and Close 1971; Close 1972) and in vivo for human muscles (Ikai and Fukunaga 1968).

In the past, measurements of human muscle CSA have been carried out by anthropometric techniques both on living subjects by measuring total limb circumference, skinfold thickness and accounting for bone CSA (Heymsfield 1982; Jones and Pearson 1969) and on the amputated limbs of cadavers (Haxton 1944; Alexander and Vernon 1975). Whilst data from anatomical dissections enabled the evaluation of CSA of individual muscles or muscle groups, anthropometry on living subjects could only provide information on total muscle CSA.

The first in vivo determination of human muscle CSA was carried out on elbow flexors by Ikai and Fukunaga (1968), by ultrasonic techniques. These authors evaluated the force/CSA of this muscle group to be about $46\ N \cdot cm^{-2}$. They also found that force/CSA is independent of age and sex.

Although ultrasonic techniques are useful for distinguishing muscle, adipose and bone tissues from each other, they prove inaccurate in resolving adjacent muscles. More recently, with the introduction of Computerized Tomography, Maughan (1983a) was able to measure knee extensor CSA and calculated a stress for the quadriceps between 7.1 and $12.6\ N \cdot cm^{-2}$. This value, however, referred to quadriceps force measured at the ankle. In a following study Mc Cullagh et al. (1983), after accounting for the distance from the knee joint to the ankle, reported tension values at the patellar tendon 10 times as high as those measured at the ankle. Large differences exists among the values of force/CSA reported in the literature and careful attention should be paid to the mean-

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ing of each of these data (Table 1). If the force of a muscle group is to be standardized for its CSA (whether anatomical or physiological), only the area of the muscle(s) involved in that particular movement should be considered. Biomechanical factors must also be taken into account, as the maximum force of a muscle should be expressed in terms of force acting on its tendon and not at the site of measurement if this is elsewhere. This requires knowledge of the moment arms of the lever system under consideration.

Whereas several studies have been carried out to determine the force/CSA of human knee extensor muscles, few studies concerning knee flexors exist. The lack of data on this muscle group may be attributable to the difficulty in distinguishing flexor muscles from the adjoining adductors using the techniques available so far (ultrasounds and CT-scans). Since the introduction of Nuclear Magnetic Resonance (NMR) imaging, by virtue of its high resolution power, it has become possible to clearly identify individual muscles from muscle groups as well as other components such as nervous, adipose and bone tissue.

The aim of the present study was to compare the force/CSA of muscle groups which apparently present differences in absolute force, such as knee extensors and flexors.

Materials and methods

Six healthy male volunteers participated in this investigation. The subjects had a mean (±sd) age of 27.8±3.5 years, body weight 74.8±9.8 kg and height 178±2.5 cm. All subjects were informed of all possible risks of the study and gave their written consent to participate.

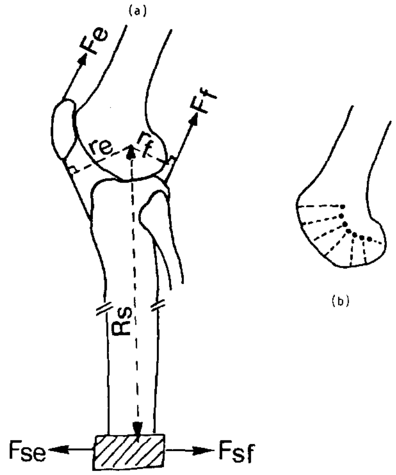


Fig. 1a. The force in the quadriceps (Fe) and hamstrings (Ff) tendons is calculated from the moment equilibrium equation: $Ft \cdot r = Fs \cdot Rs$ where Ft = force in the tendon, r = radius from the centre of rotation of femur condyl to the tendon, Fs = external force measured at the ankle, Rs = distance from the centre of rotation of the condyl to the point of application of the external force. **b.** The centre of rotation of the femoral condyl changes during joint motion.

CSAs of the dominant leg (right in all subjects) were measured by NMR imaging (Gyroscan S5 Philips Superconductive 0.5 TESLA system). The frequency of the magnetic field was 21.4 MHz and transverse slices were 10 mm thick (integral). CSA of individual muscles of the extensor and flexor groups were calculated by the planimetric area weighing technique. In order to evaluate maximum knee extensor and flexor CSA, NMR axial scans were carried out at five levels of the thigh, each separated by 5 cm.

CSA of extensor muscles was calculated from the sum of vastus lateralis, medialis, intermedius and rectus femoris, whereas CSA of flexor muscles was calculated as the sum of biceps femoris, semitendinous, semimembranous, gracilis and sartorius individual cross-sections.

Table 1. Stress and cross sectional area (CSA) of different muscle groups reported in the literature

Muscle group	CSA cm^2	Stress $N \cdot cm^{-2}$	Reference	Year
Elbow flexors	14.8	100.0	Fick	1910
Elbow flexors	18.4	108.9	Franke et al.	1920
Elbow flexors	9.2	23.3	Ralston et al.	1949
Elbow flexors	27.3	46.1	Ikai & Fukunaga	1968
Elbow flexors	10.1	33.0	Nygaard et al.	1983
Ankle flexors	114.7	61.2	Hermann et al.	1898
Ankle flexors	110.6	51.5	Reys et al.	1915
Ankle flexors	112.9	38.2	Haxton et al.	1944
Knee extensors	74—110	58—70	Tsunoda et al.	1983
Knee extensors	79.0	86.2	Mc Cullagh et al.	1983
Knee extensors	87.0	42.2	Wickiewicz et al.	1985
Knee extensors	83.9	80.1	Present study	1987
Knee flexors	42.0	78.9	Wickiewicz et al.	1985
Knee flexors	43.5	70.5	Present study	1987

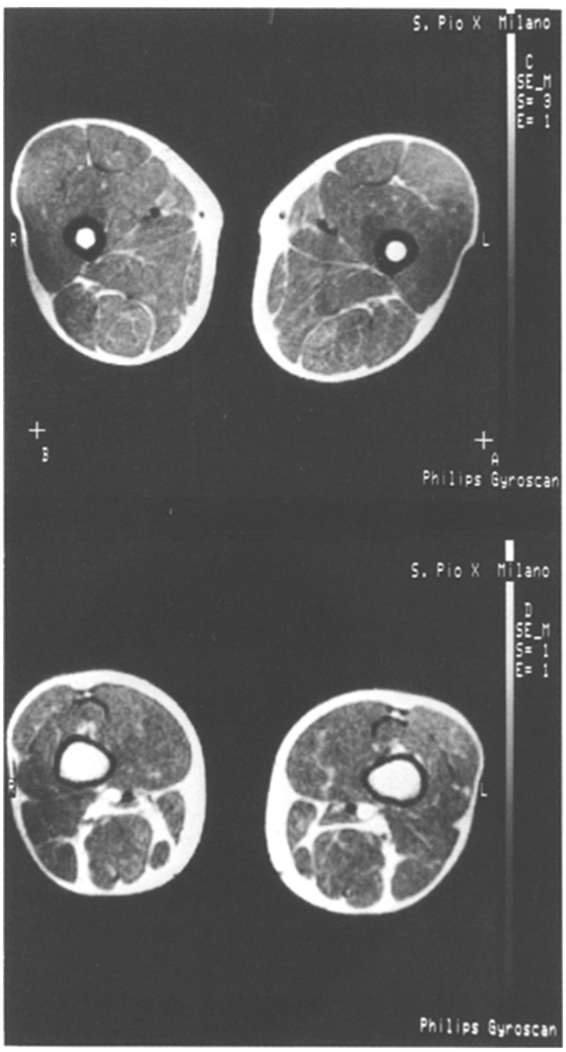
Isometric muscle strength was measured in the sitting and supine positions, using an isokinetic dynamometer (Cybex II, Lumex INC, N.Y.), throughout a range of knee angles from 90° to full extension (180°) at 10° steps. The subject was positioned in a reclining experimental chair with the dominant leg attached to the lever arm of the dynamometer. Care was taken that the pivot point of the lever arm was aligned with the rotation axis of the knee joint. For each subject the distance from the centre of rotation of the femoral condyle to the point of application of external resistance was measured. In order to evaluate the knee angles at which the maximum isometric torque (MIT) of the extensors and the flexors is at its highest, subjects were asked to perform, after a brief period of warm-up, three maximum voluntary contractions, each set at steps of 10° throughout an angular range between 90° and 180° (full extension); out of each set, the highest value was chosen for data analysis. On a different day, MIT of extensors and flexors was only measured at the optimum angles, with a set of five contractions, carried out with the maximum possible effort; out of these, the highest value was chosen for data analysis.

In both experimental conditions, the duration of each contraction was standardized to 5 seconds and 1 min interval was allowed in between, a time which is sufficient for full recovery of muscle strength (Simonson 1971).

In order to account for the effect of gravity on the torque produced, the gravitational moment of the leg and the lever arm were measured isometrically at 10° steps throughout a range between full extension and 90°. Correction of torque for gravity was obtained either by subtracting (in case of flexion) or adding (in case of extension) the gravitational moment of the leg including the lever arm which was calculated by multiplying the torque (Nm) by the cosine of the angle (180-θ), where θ is the angle between tibia and femur. Conversion of torque values (Nm) to force values (N) was carried out by dividing torque measurements by the moment arm of the external force (Rs).

In order to calculate the tension in the knee extensor and flexor muscles from the moment equilibrium equation, the following variables must be measured: a) the moment arm for the patellar ligament (re) and the hamstrings tendon (rf); b) the moment arm for the external force (Rs) and c) the external force of extensor (Fse) and flexor (Fsf) groups (Fig. 1). While Rs and Fse and Fsf were directly measured for all our subjects, re and rf were obtained from the literature (Smidt 1973) as no statistical difference between the anthropometric characteristics (age, height, weight, tibial and femur length and thigh circumference) of the present subjects and those of Smidt's study was found.

Differences between force, CSA and force/CSA of flexor and extensor muscles were assessed by means of the paired Student t-test; level of significance was chosen at $p < 0.05$.



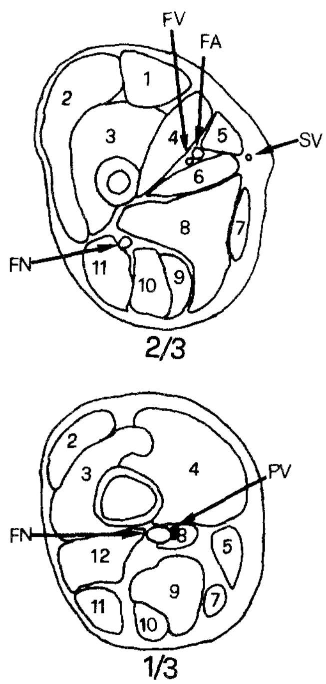


Fig 2a. Axial NMR imaging scans at 1/3 lower and 2/3 upper femur height. **b.** The high resolution power of NMR enables the identification of individual muscles, blood vessels and nerves. 1: rectus femoris, 2: vastus lateralis, 3: vastus intermidius, 4: vastus medialis, 5: sartorius, 6: adductor longus, 7: gracilis, 8: adductor major, 9: semimembranous, 10: semitendinous, 11: biceps femoris (long head), 12: biceps femoris (short head). FA: femoral artery, FV: femoral vein, SV: saphenous vein, PV: popliteal vein, FN: femoral nerve

Table 2. Cross-sectional areas (mean ± sd) at 2/3 upper femur and 1/3 lower femur height

CSA	2/3 upper femur height cm^2	1/3 lower femur height cm^2
Total	212.9 ± 43.4	154.0 ± 24.7
Muscle + bone	176.6 ± 28.8	117.0 ± 12.8
Muscle − bone	169.3 ± 28.2	107.9 ± 13.1
Extensors	83.9 ± 14.3	59.4 ± 8.3
Flexors	26.8 ± 6.3	43.5 ± 7.2

Table 3. Maximum isometric strength and cross-sectional area of knee extensor and flexor muscles and their respective stress

	Extensors	Flexors	$p<$
Maximum isometric torque corrected for g (Nm)	312.4 ± 22.2	115.5 ± 17.4	0.001
Force at ankle (N)	876.8 ± 74.4	326.6 ± 54.6	0.001
Force along tendon (N)	6620.4 ± 470.4	2809.9 ± 272.7	0.001
Cross-sectional area (cm^2)	83.9 ± 14.3	43.5 ± 7.2	0.001
Stress ($N \cdot cm^{-2}$)	80.1 ± 15.5	70.5 ± 7.0	n.s.

Results

By carrying out scans at five evenly spaced levels along the thigh, the maximum anatomical CSA of the extensor muscles was found to be at 2/3 upper femur height while the maximum CSA of the flexors was at 1/3 lower femur height (Table 2 and Fig. 2). At the upper 2/3 femur height the extensors occupied 38.2% of the total limb CSA, while the flexors occupied 12.2%; at 1/3 lower femur height the extensors occupied 38.6% and the flexors 28.2%. The CSA of the extensor muscles was found to be significantly greater than that of the flexors at both levels measured ($p<0.001$). However, the flexor/extensor CSA ratio increased distally: 0.32 at 2/3 upper femur height ($p<0.005$) and 0.73 at 1/3 lower femur height ($p<0.001$).

No statistical difference between MIT in the sitting and supine position was found for the extensors, while MIT of the flexors was significantly greater in the sitting position ($p<0.05$). Therefore MIT in the sitting position was chosen for data analysis.

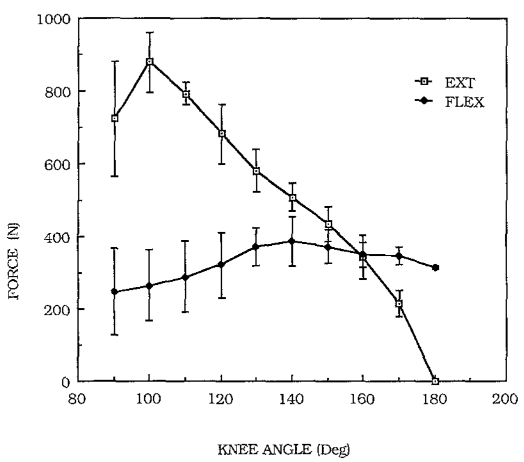


Fig. 3. Maximum isometric forces (means ± 1 s.d., $n=6$) of knee extensors *(EXT)* and flexors *(FLEX)* at different knee angles between 90° and 180° (full extension)

The maximum isometric external force generated by the extensors and flexors was 876.8 ± 74.4 N (at 100°) and 326.6 ± 54.6 N (at 140°), respectively (Fig. 3). The calculated tensions in the quadriceps and hamstring tendons were 6620.2 ± 470.4 and 2809.9 ± 272.7 N, respectively ($p<0.001$).

When the tension in the muscles was standardized for their respective maximal CSA, the resulting stress was 80.1 ± 15.5 $N \cdot cm^{-2}$ for the extensors and 70.5 ± 7.0 $N \cdot cm^{-2}$ for the flexors and no statistically significant difference was found between the two muscle groups (Table 3).

Discussion

Nuclear Magnetic Resonance imaging enables accurate in vivo determinations of CSA of individual muscles. Whereas in the past, with the use of Computer Tomography (CT) the CSA of a muscle group e.g. knee extensors (Maughan 1983) could be measured, no techniques were available to clearly differenciate between adjoining muscles, and thus measurements of CSA of individual muscles proved difficult.

NMR compared to CT-scans presents three distinct advantages. The main advantage is related to the orientation of scanning planes: while by CT it is only possible to scan in axial planes, by NMR, scans in axial, coronal, sagittal and oblique planes can be directly obtained without the need to move the subject. Another advantage is that, while CT is based on differences in tissue density (and thus transmission or absorbance of X-rays), the NMR signal depends on various parameters (such as proton density, relaxation time, etc.), depending on the molecular characteristics of the tissue. The NMR signal is, therefore, tissue specific and by virtue of this, has a greater power of differentiation between tissues, even between those which result indistinguishable by CT-scans because of very similar densities. Besides, NMR does not involve ionizing radiations.

Adjoining tissues such as muscular, adipose and connective tissues are differentiated by NMR through a sequence of impulses (modality of aquisition). Indeed it was possible to distinguish between adjacent muscles e.g. adductor muscles from hamstrings, even in thin subjects with very little connective and adipose tissue.

The knee extensor muscles appear to generate considerably greater values of force than the knee flexors. This difference in strength is most probably a direct effect of the larger CSA of the extensors compared to that of the flexors, as it is commonly agreed that the maximum force of a muscle depends on its CSA (Fick 1910; Haxton 1944; Ikai and Fukunaga 1968). The present MIT values are in good agreement with those reported by several authors on knee extension (Knapik and Ramos 1980; Larsson et al. 1979; Thorstensson et al. 1976).

The mechanical advantage, calculated from the ratio of the external force to the tension in the tendon, was found to be 0.132 ± 0.005 for the extensors and 0.116 ± 0.012 for the flexors. Thus there seems to be a 13.8% difference in mechanical advantage in favour of the flexor muscles, which is explained by the smaller moment arm of the latter (4.08 cm at an angle between femur and tibia of 140°) as compared with the former (4.72 cm at an angle of 100°). The values of mechanical advantage found for the knee extensors are comparable to those reported by Maughan (1983a).

The present study has shown that not only are the extensor muscles considerably stronger than the flexors but also that their anatomical CSA is significantly different. The maximum anatomical CSA of the knee extensors was found to be similar to that reported in previous studies (Maughan 1983; Maughan 1983a; Maughan and Nimmo 1984; Schantz et al. 1983; Tsunoda et al. 1983). Little data on flexor CSA was found in the literature, however in a recent paper Wickiewicz et al. (1985) reported a CSA of knee flexors, in cadaver limbs of 42 cm^2.

It was shown that no significant difference in force/CSA exists between flexors and extensors. This suggest that in vivo force/CSA is not different in antagonist muscle groups. This finding does not agree with the results of Wickiewicz et al. (1985) who reported a force/CSA of 42.4 $N \cdot cm^{-2}$ for knee extensors and 78.9 $N \cdot cm^{-2}$ for knee flexors.

These authors reported CSAs of knee extensor and flexor muscles which are very comparable to ours, but their values of maximum force refer to measurements under isokinetic conditions and at knee angles (thus muscle length) which are very different from those at which maximum force occurs under isometric conditions.

The present values of force are expressed in terms of anatomical CSA and are comparable to the data obtained in the same muscles by other workers following the same approach (table 1). Different values were reported by Haxton (1944) on the calf muscle (38 $N \cdot cm^{-2}$) and by Ikai and Fukunaga (1968) on the arm flexors (46 $N \cdot cm^{-2}$). The above values were obtained by expressing force measurements per unit of physiological CSA, which in the case of a unipennate muscle such as the calf muscle is the sum of the CSAs perpendicular to the muscle fibres along the whole length of the muscle, and in the case of the biceps brachii, a parallel-fibre muscle, corresponds to its anatomical CSA.

Alexander and Vernon (1975) measured on a male cadaver the angle of pennation of the quadriceps muscles, their mass, the distance between the tendon of origin to the tendon of insertion and assuming a density of muscle of 1050 kgm^{-3}, evaluated a physiological CSA of 135 cm^2. In accordance with the data of the above study, considering an average angle of pennation for the quadriceps of 15.2°, a mean distance between tendons of 20 mm, and a muscle mass of 1.33 kg, i.e. 1.8% of our subjects mean body weight (from Alexander data), from the present data a theoretical physiological CSA for the quadriceps of 160 cm^2 is obtained, which is approximately twice the measured anatomical section.

As we calculated a force acting on the quadriceps tendon of 6620 N, is total component in the fibres would be 6620 $\cos^{-1}$ 15.2°, i.e. 6860 N, which divided by a physiological CSA of 160 cm^2 would give a stress of 42.9 $N \cdot cm^{-2}$. This theoretical value is indeed very close to those reported by Haxton (1944) and Ikai (1968). A considerable difference indeed exists between the physiological and anatomical CSA of pennate muscles (Rays 1915; Franke 1920; Haxton 1944). As a matter of fact, physiological CSA not only depends on the angle of pennation and distance between tendons but also on muscle length.

These values of stress of human skeletal muscle seem considerably greater than those found in the literature for other mammals. Most animal studies report values of stress between 10 and 30 $N \cdot cm^{-2}$. No clear explanation is yet available to account for these differences. Fibre composition is an unlikely candidate, as the gastrocnemius of man and other mammals have very similar fiber composition, but different strengths (Ariano 1973; Haxton 1944; Spector 1980). Besides, recent evidence suggests that muscle fibre composition does not play a determinant role in maximum isometric force and thus cannot account for differences in force/CSA (Saltin and Gollnick 1983).

Architectural characteristics such as pennation angle or muscle fibre to muscle length ratio could be possible candidates. The ratio of fibre to muscle length is indeed different when the semitendinous of human and cat are compared (Alexander and Vernon 1975; Bodine et al. 1982).

In conclusion, this study has shown that the maximum force per unit of the anatomical CSA of knee extensor and flexor muscles is virtually the same, i.e. 80 $N \cdot cm^{-2}$ and 70 $N \cdot cm^{-2}$, respectively; these values appear to be nearly twice the stress expressed in terms of physiological CSA.

Acknowledgements. The authors feel very indebted to Prof. F. Saibene for valuable advice and constructive criticism.

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Accepted June 26, 1987