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Measurement of fibre pennation using ultrasound in the human quadriceps in vivo

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Summary. Real-time ultrasound scanning was used to measure the angles of fibre pennation of vastus lateralis (VL) and vastus intermedius (VI) of the human quadriceps ($n = 12$) in vivo. The maximum isometric force and cross-sectional area of the quadriceps were also measured. With the knee at right-angles the mean fibre angles for VL and VI respectively were 0.133 (0.021) rad [7.6° (1.2°)] and 0.143 (0.028) rad [8.2° (1.6°)] [mean (SD)], which is within the range of angles measured on cadavers. The mean angle decreased in going from the contracted [VL, 0.244 rad (14°); VI, 0.279 rad (16°)] to the stretched [VL, 0.105 rad (6°); VI, 0.122 rad (7°)] position. There was a significant positive correlation between fibre angle and muscle cross-sectional area but no relationship between fibre angle and force per cross-sectional area. No increase in fibre angle was detected after 3 months strength training. We conclude that ultrasound can be used to measure pennation angles of superficial muscle groups but we could not demonstrate a relationship between pennation and force-generating capacity.

Key words: Skeletal muscle – Pennation – Specific tension – Ultrasound – Strength training

Introduction

There are many reports in the literature of the specific force (i.e. strength per unit area) for human muscles (see Narici et al. 1988) with values for the quadriceps around 700 kN m^{-2}. Between individuals there can be up to a twofold variation in values for a given muscle (e.g. Maughan et al. 1983; Rutherford 1986). Several studies have now demonstrated a fall in specific force with age (Bruce et al. 1989; Jones and Rutherford 1990; Pearson et al. 1985) and an increase with strength training (Jones et al. 1989) but the cause of these changes remains unexplained. The specific tensions measured in isolated animal muscle are much lower than those found in humans [100–300 kN m^{-2} (Close 1972)]. A major part of the discrepancy between the human and animal work is known to be the difficulties of measuring the true physiological cross-section of the fibres in a human pennate muscle. Conventional scanning techniques, such as computerised tomography (CT), nuclear magnetic resonance imaging (NMRI) and ultrasound, all measure the muscle cross-section at right angles to the limb i.e. the anatomical cross-sectional area (CSA). In a complex pennate muscle group, such as the quadriceps, this will substantially underestimate the total area of the fibres in parallel.

Studies on human cadavers have found pennation angles in the quadriceps of 0.227–0.314 rad (13–18°) (Alexander and Vernon 1975) and 0.087–0.785 rad (5–45°) (Wickiewicz et al. 1983). Giannini et al. (1990) have used NMRI to measure pennation in vivo in humans. The other technique that could potentially provide this information is ultrasound. Ultrasound waves are reflected back from the collagen-rich connective tissue between fascicles and the angle between these and the deep fascia between muscle groups gives the angle of the muscle fibres to the line of action of force of the muscle.

The functional consequences of pennation will be twofold. First, the force produced in the tendon by the contraction of the fibres will be less than the sum of the forces produced in the individual fibres. The force resolved in the tendon will be proportional to $\cos\alpha$ (where α = angle of pennation). A second, beneficial, consequence of this pennation is that more contractile material can be placed in parallel for a given anatomical cross-section. The relationship between the force resolved in the tendon, the amount of contractile material and the angle of pennation is complex. Alexander and Vernon (1975) proposed a model in which the force in the tendon was proportional to $\sin 2\alpha$, which predicts that the tendon force would increase up to an angle of 0.785 rad. The angle could therefore affect the force generated for a given anatomical cross-section of muscle.

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There have been no studies looking at the functional significance of variations in pennation angles for force generation in humans. In this study we have used ultrasound scanning to measure the angle of pennation of v. lateralis and v. intermedius of the human quadriceps in vivo. We have then investigated the relationship between these angles and the CSA and force/CSA of the quadriceps, both before and after a period of high-resistance weight training.

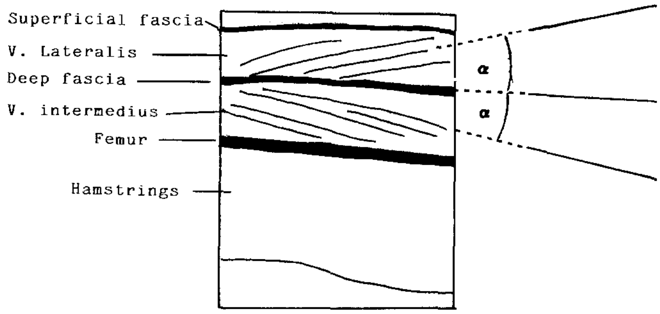

Fig. 1. Drawing taken from ultrasound scan showing measurement of pennation angle (α)

Methods

Subjects. A total of 12 subjects were studied (7 male, 5 female), 4 of whom took part in regular training for power events such as high-jumping and sprinting. Anthropometric details for the subjects are given in Table 1. Six of the more sedentary subjects took part in 3 months of high-resistance weight training. All subjects gave their written consent to participate and the study was approved by the Committee for the Ethics of Human Investigations, University College and Middlesex School of Medicine.

Ultrasound scanning. A Hitachi EUB 25 real-time scanner with a 3.5-MHz linear-array transducer was used to take sagittal ultrasound pictures of vastus lateralis (VL) and vastus intermedius (VI). Measurements were not made on v. medialis and rectus femoris because the scans obtained from these muscles were very difficult to interpret. With the head of the probe perpendicular to the fasciculi the fibre bundles can be seen as a striated pattern lying at an angle to the surface of the muscle. The probe was placed directly on the skin and transmission gel was used to aid acoustic coupling. Subjects were scanned at half femur height and two or three scans were taken on each occasion with the hip and knee at right-angles. In some subjects scans were also taken with the knee in full extension, quadriceps contracted, and with the quadriceps stretched (knee fully flexed). The angle (α) between the striations and the fascia between VL and VI was measured as shown in Fig. 1 and taken as the angle of pennation. The distance between striations averaged 2-5 mm, which is of the same order of size as the larger muscle fascicles in the quadriceps.

To calculate the coefficient of variation (CV) of the measurement 7 subjects had repeat measurements 1-3 weeks apart. The results are illustrated in Fig. 2 and the CV was found to be 13.5%.

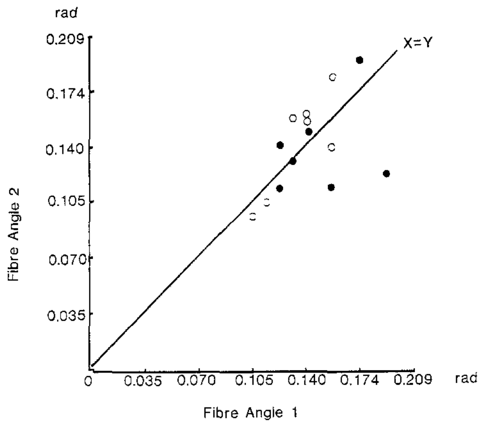

Fig. 2. Correlation between repeat scans on 7 subjects for vastus lateralis (VL; ●) and vastus intermedius (VI; ○)

Quadriceps strength. The maximum voluntary isometric contraction strength (MVC) of the quadriceps was measured using a conventional strength-testing chair in which the subject was seated with the hip and knee at right angles (Edwards et al. 1977). The best of three values was measured at each test. During the manoeuvre a percutaneous twitch superimposition technique (Rutherford et al. 1986) was used to test whether subjects could maximally activate their quadriceps during the isometric contraction.

Quadriceps cross-sectional area. Quadriceps CSA was measured from a CT X-ray scan taken at half femur height. Scans were performed on a Philips Tomoscan 350 and the images analysed offline on a locally developed interactive medical-imaging package (Grindrod et al. 1983). Subjects were supine with the legs straight during scanning. Muscle area was measured semi-automatically with a contour-following programme and manual editing. The coefficient of variation for the repeat scanning of the quadriceps muscle was below 4%. The force-generating capacity of the muscle was calculated as the ratio MVC/CSA. CSA data were available for 11 of the subjects.

Table 1. Anthropometric details for group

Parameter	Mean	Range
Age (years)	27	18–40
Height (m)	1.74	1.63–1.91
Weight (kg)	69.5	63.3–83.0

Training protocol. Subjects trained the quadriceps muscle on a leg-extension machine (Atlanta Sports, Rotheram, UK) three times a week for 12 weeks; each session consisted of four sets of six repetitions at a weight that could just be lifted six times. Quadriceps MVC, CSA and fibre angles were measured before and after the training period.

Results

The mean angle of pennation for the group with the knee at right angles was 0.133 (SD 0.021) rad (range 0.105–0.166) and 0.143 (SD 0.028) rad (range 0.122–0.213) for VL and VI respectively. In going from the shortened and contracted to the stretched position the mean angle changed from 0.244 rad (VL) and 0.279 rad (VI) to 0.105 rad (VL) and 0.122 rad (VI). The variation between fasicles ranged from 0.009 rad to 0.017 rad; therefore the mean for two to three fasicles was taken for each subject. There was no significant difference be-

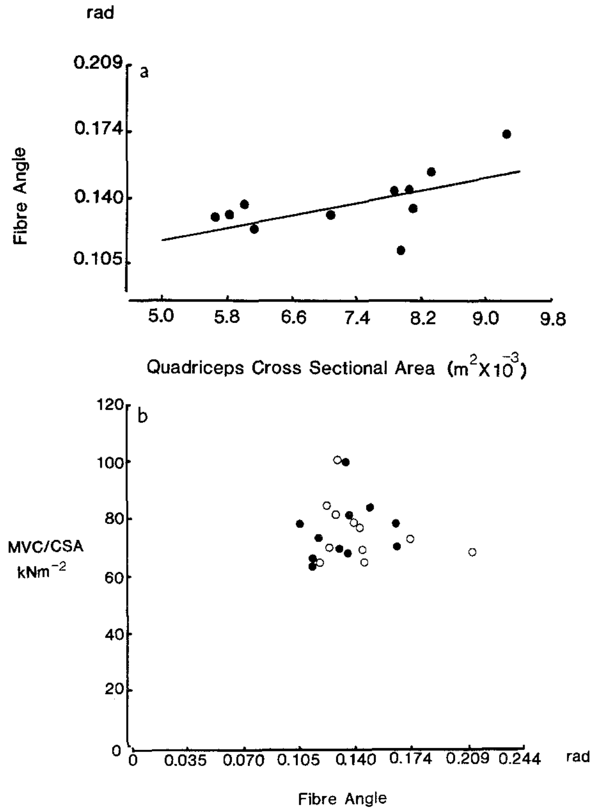

Fig. 3. a Relationship between quadriceps-cross sectional area and fibre angle (taken as mean for VL and VI) ($r = 0.63$; $P < 0.05$). **b** Scatterplot of fibre angle with force per unit area. ●, VL; ○, VI

tween the angles for the right and left legs, or between the angles for men and women.

All subjects were able to activate their quadriceps muscle maximally as demonstrated by the twitch-superimposition technique. There was a significant positive correlation between the quadriceps CSA and the angle of pennation (taken as a mean of the absolute values for VL and VI; Fig. 3a). The specific forces (MVC/CSA) ranged from 65 kN m^{-2} to 100 kN m^{-2}, with no significant difference between the male and female subjects. There was no relationship between MVC/CSA and α (Fig. 3b). Group mean data for quadriceps strength, CSA and angles of pennation are given in Table 2.

Training

There were significant increases in MVC, CSA and MVC/CSA after the 12 weeks of training but no change in α for either VL or VI (Table 3).

Discussion

The in vivo pennation angles measured in this study for VL and VI in the shortened/contracted position were similar to those measured by Alexander and Vernon (1975) in one male cadaver (VL, 0.227 rad; VI, 0.314 rad) and within the range measured by Wickiewicz et al. (1983) on three cadavers (0.087–0.785 rad, VL and VI). There are, however, several problems associated with such measurements on cadavers. For example there are likely to have been changes to the muscle architecture during the fixation process, which could alter the fibre angles from their values in vivo. In the study of Wickiewicz et al. (1983) no data on the age or prior medical/activity history of the subjects was provided and these could possibly also alter muscle architecture.

Giannini et al. (1990) found values very similar to those of the present study. They used NMRI to visualise all four constituent muscle groups of the quadriceps in vivo. Their subjects were men aged 27–36 years who took part in regular physical exercise. The angles of pennation for the VL and VI, respectively, were in the range 0.209–0.471 rad and 0.297–0.419 rad with the leg straight and the muscle relaxed. In an expanded study the same group found mean angles of 0.298 (SD 0.073) rad (VL) and 0.332 (SD 0.105) rad (VI) (Narici et al. 1992). These are in good agreement with our measurements with the leg straight and the muscle contracted (VL, 0.174–0.305 rad; VI, 0.166–0.471 rad). Recently Henriksson-Larsen et al. (1992) reported pennation angles for VL, using ultrasound, in a small group of wo-

Table 2. Group mean data for quadriceps strength, size, specific force and pennation angle

Parameter[a]	Mean	SD	n
Quadriceps strength (N)	548	108	11
Quadriceps CSA ($m^2 \times 10^{-3}$)	7.27	1.19	11
MVC/CSA (kN m^{-2})	75	10	11
VL angle (rad)			
Knee at right-angle	0.133	0.021	12
Stretched	0.105	—	3
Contracted	0.244	0.052	5
VI angle (rad)			
Knee at right-angle	0.143	0.028	11
Stretched	0.122	0.052	4
Contracted	0.279	0.122	6

[a] CSA, cross-sectional area; MVC, maximum voluntary isometric contraction strength

Table 3. Quadriceps strength (MVC), cross-sectional area (CSA), specific force (MVC/CSA) and fibre angles before and after 12 weeks of strength training[a]

Parameter	Before training		After training	
MVC (N)	517	(118)	587	(139)**
CSA ($m^2 \times 10^{-3}$)	6.75	(1.04)	7.06	(1.04)**
MVC/CSA (kN m^{-2})	76	(13)	82	(12)*
Fibre angle (rad)				
VL	0.139	(0.021)	0.136	(0.028)
VI	0.141	(0.024)	0.143	(0.024)

[a] Results are means (SD)
* $P < 0.05$; ** $P < 0.01$

men. Their values for the quadriceps contracted (0.349–0.436 rad) were higher than those found in this study, although their mean level with the muscle relaxed was very similar to ours (0.192 rad). Their measurements were made at a higher level in the muscle and the position of the leg was not stated.

The ultrasound technique was sensitive enough to measure increases in fibre angles going from the stretched/relaxed to shortened/contracted position. A decrease from 0.133 rad to 0.105 rad when changing from the knee at right-angles to fully stretched, would be consistent with a length change of the muscle from 0.3 m to 0.38 m.

One problem with this technique was knowing the exact position in the muscle when the scan was being taken. Although the probe was always placed at half femur height the exact lateral position was much harder to locate unless there was a distinguishing mark on the leg. The probe itself was quite large (approximately 3.6×10^{-3} m^2) and slipped easily on the gel. Consequently it was difficult to scan at exactly the same position on each occasion. The CV for repeat measurements was found to be 13.5%, which would only allow for variations of about 0.035 rad to be measured with any degree of confidence.

The force/CSA for the group ranged from 65 kN m^{-2} to 100 kN m^{-2}. The lower values could not be explained by submaximal activation of the quadriceps since it was demonstrated by the twitch-superimposition technique that the subjects were able to produce maximum contractions. The force measured was that generated at the ankle through the lever system of the knee and lower leg. Assuming a mechanical advantage of 0.132 (Narici et al. 1988; Smidt 1973), the forces generated in the patellar tendon would be 4515 N giving a specific force of 621 kN m^{-2} (calculated using the *anatomical* CSA). This value is comparable to those previously reported in the literature for the quadriceps.

An increased angle of pennation might be expected as a result of muscle hypertrophy (Gollnick et al. 1981) and in support of this we have found a significant positive correlation between fibre angle and anatomical CSA. The larger the angle of pennation the greater the number of sarcomeres that could be arranged in parallel and therefore the greater the force generated during a contraction. Expressing the specific force as the strength per unit anatomical cross-section would underestimate the physiological cross-sectional area and result in an apparently greater force/CSA. In our small group, however, there was no correlation between fibre angle and the specific force. This might be due to the technique not being sensitive enough to measure small differences in angle between people or the fact that angles were measured on only two of the four constituent muscles of the quadriceps. Alternatively the differences in force/CSA may arise because of variations in factors other than fibre angle, such as intramuscular fat or fibre-type content.

With strength training the muscle anatomical CSA increased on average by 4.7%, strength by 12.8%, and force/CSA by 7.7%. If there was an increase in the angle of pennation accompanying fibre hypertrophy, then the real increase in physiological CSA could be underestimated by measuring the anatomical cross-section. This could account for the apparent increase in the force/CSA. There was no evidence, however, from this study that there was a change in pennation angle after 3 months of training. Using the model of Alexander and Vernon (1975) it can be estimated that to obtain a 12.8% increase in strength, with only a 4.7% increase in anatomical CSA, would require an increase in the angle of pennation of about 8%. This would mean a change from 0.14 rad before training to 0.15 rad after training. The ultrasound technique may not be sufficiently sensitive to detect such small angular changes.

In conclusion we have shown that ultrasound scanning can be used to measure pennation angles in superficial muscle groups and gives similar values to those measured on cadavers. The technique was able to detect the expected change in fibre angle when muscle length was changed. The larger muscles had greater angles of pennation but we could not demonstrate a relationship between fibre angle and force-generating capacity or a change in pennation angles with strength training.

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