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# STRENGTH AND CROSS-SECTIONAL AREA OF HUMAN SKELETAL MUSCLE

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## SUMMARY

1. The maximum voluntary force (strength) which could be produced by the knee-extensor muscles, with the knee held at a right angle, was measured in a group of healthy young subjects comprising twenty-five males and twenty-five females. Both legs were tested: data from the stronger leg only for each subject were used in the present study.

2. Computed tomography was used to obtain a cross-sectional image of the subjects' legs at mid-thigh level, measured as the mid-point between the greater trochanter and upper border of the patella. The cross-sectional area of the knee-extensor muscles was determined from the image obtained by computer-based planimetry.

3. The subjects' height and weight were measured. An estimate of body fat content was obtained from measurements of skinfold thicknesses and used to calculate lean body mass.

4. Male subjects were taller ($P < 0.001$), heavier ($P < 0.001$), leaner ($P < 0.001$) and stronger ($P < 0.001$) than the female subjects. No significant correlation was found to exist between strength of the knee-extensor muscles and body weight in the male or in the female subjects. In the male subjects, but not in the female group, there was a positive correlation ($r = 0.50$; $P < 0.01$) between strength and lean body mass.

5. Muscle cross-sectional area of the male subjects was greater than that of the female subjects ($P < 0.001$). The ratio of strength to cross-sectional area for the male was $9.49 \pm 1.34$ (mean ± S.D.). This is greater but not significantly so, than that for females ($8.92 \pm 1.11$). In both male and female groups, there was a significant ($P < 0.01$) positive correlation between muscle strength and cross-sectional area.

6. A wide variation in the ratio of strength to muscle cross-sectional area was observed. This variability may be a result of anatomical differences between subjects or may result from differences in the proportions of different fibre types in the muscles. The variation between subjects is such that strength is not a useful predictive index of muscle cross-sectional area.

## INTRODUCTION

It is widely accepted that the maximum force which can be produced by a muscle is directly proportional to its cross-sectional area (Knuttgen, 1976). *In situ* measurement of muscle cross-sectional area in intact healthy individuals was first made possible by the development of ultrasonography. Using this method, Ikai & Fukunaga (1968) found a positive relationship between cross-sectional area and maximum isometric strength of m. biceps brachii. The population studied comprised a large number ($n = 245$) of young (12–30 years) subjects, with approximately equal numbers of males and females. More recently, Young, Stokes, Walker & Newham (1981) have used a similar ultrasonic technique to measure the cross-sectional area of the knee extensor muscles in a smaller, ($n = 25$) older, (19–48 years) population, again containing approximately equal numbers of males and females. They reported a strong ($r = 0{\cdot}84$) positive correlation between cross-sectional area and strength of the quadriceps, with no difference between male and female subjects.

The development of computed tomography has enabled cross-sectional images of human limbs to be obtained with a much higher degree of resolution than can be obtained using ultrasonography (Ferrucci, 1979). This technique has previously been used to determine the cross-sectional area of muscle groups in normal intact humans (Haggmark, Jansson & Svane, 1978; Bulcke, Termote, Palmers & Crolla, 1979). The aim of the present study was to use the superior image resolution provided by computed tomography to measure the cross-sectional area of the knee extensor muscles in a normal healthy adult population and to relate these measurements to the maximum isometric force which could be exerted by that muscle group. The relationship between muscular strength and other anthropometric parameters in the same group has also been investigated.

## METHODS

Fifty normal healthy young adult subjects participated in this study, twenty-five males and twenty-five females. Details of the physical characteristics of the subjects are presented in Table 1. Body fat content was determined according to the method of Durnin & Ramahan (1967) and was used to determine lean body mass. None of the subjects could be considered to be highly trained, but several took part in some form of regular physical activity, whereas others were totally sedentary.

Measurements were made on both legs of all subjects. Computed tomography was used to obtain a cross-sectional image of the leg at mid-thigh level as described below. Immediately following this, the maximum isometric force which could be exerted by the knee-extensor muscles of each leg was determined.

All subjects were fully informed of the purpose of the study and of the possible risks involved before giving their written consent to participate. Although the radiation dose to which the subjects were exposed as a result of the computed tomography scanning is extremely small (Perry & Bridges, 1973) and does not represent a significant hazard, full lead apron protection for shielding of gonads and virtually all bone marrow was given. This study was approved by the Joint Ethical Committee of Aberdeen University and Grampian Health Board.

### *Determination of muscle strength*

Muscle strength was measured as the maximum voluntary force which could be exerted by the knee extensor muscles with the knee held at a right angle. The apparatus used was similar to that described by Tornvall (1963) and is illustrated in Fig. 1. The movable back support was adjusted

TABLE 1. Physical characteristics of male and female subjects

| | Males ($n = 25$) | | | Females ($n = 25$) | | |
|---|---|---|---|---|---|---|
| | Mean | S.D. | Range | Mean | S.D. | Range |
| Age (years | 28·0 | 5·4 | 20·2–38·5 | 25·1 | 3·8 | 20·0–36·0 |
| Height (cm) | 174·0 | 5·3 | 160·0–182·5 | 165·2 | 7·7 | 152·0–178·5 |
| Weight (kg) | 71·7 | 9·5 | 55·9–89·4 | 59·8 | 9·0 | 47·2–89·7 |
| Body fat (%) | 16·2 | 5·3 | 9·6–28·6 | 27·1 | 4·2 | 18·5–33·8 |
| Lean body mass (kg) | 59·3 | 6·3 | 49·4–72·2 | 43·5 | 6·0 | 34·5–60·3 |

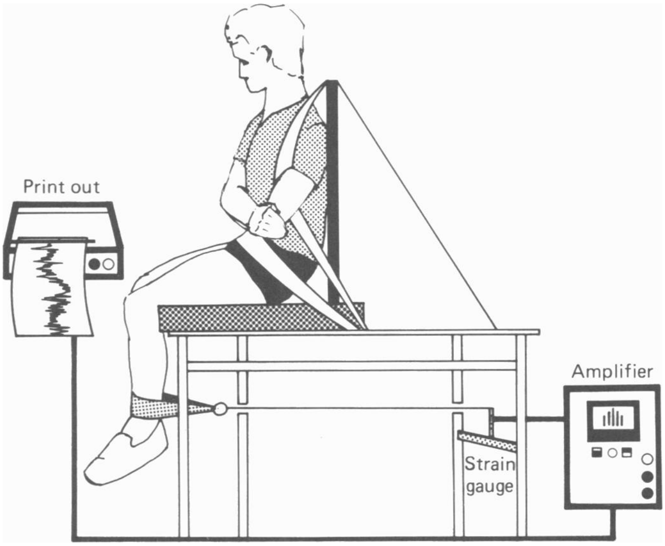

Fig. 1. Apparatus used for the determination of the maximum voluntary force which could be exerted by the knee extensor muscles. See text for explanation.

so that the back of the knee was positioned at the front edge of the chair and the subject's back was supported in an upright position. The subject was restrained with an adjustable harness which was securely fastened to prevent the tendency of the hip joint to extend when the quadriceps was contracted. A broad strap was positioned around the lower leg, immediately proximal to the malleoli. The strap was attached via a light inelastic wire to a steel plate fixed rigidly to the rear of the chair. Distortion of this plate was measured by four strain gauges arranged to form a Wheatstone bridge circuit; the amplified output of this circuit was displayed on a pen recorder. Each subject was normally given three attempts to produce a maximum contraction and the best result was recorded for each leg. The difference between the two best efforts with each leg was small, the coefficient of variation being 2·5 %, which is similar to the variability reported by Edwards, Young, Hosking & Jones, (1977) for this measurement.

*Measurement of muscle cross-sectional area*

Computed tomography is an X-ray scanning technique which produces a cross-sectional image of an object placed within the instrument. All scans in the present study were performed using an Elscint instrument, model EXel CGT 905. Scans were performed on each leg separately at the mid-thigh level, which was taken as the mid-point between the greater trochanter and upper border of the patella. The same position was adopted by all subjects in order to minimize possible postural differences. The scan was performed on a tissue slice approximately 5 mm thick; total scanning time was 22 sec for each leg.

The clarity of the image is such that it is easy to distinguish different structures, and individual muscle groups can readily be identified (Pl. 1). The cross-sectional area of the knee extensor muscles, comprising m. rectus femoris plus the three vasti, was calculated by tracing around the image displayed on a video screen using a movable cursor. The area within the line traced was calculated by a computer-based planimetric technique. All measurements were made by the same operator. Duplicate measurements on ten legs gave a coefficient of variation for the method of determining cross-sectional area of 1·6 %. This is in agreement with the results of Haggmark *et al.* (1978) who found a coefficient of variation for duplicate measurements of 2·4 %. The mean density, a measure of the X-ray attenuation of the tissue, was also calculated automatically for the entire muscle area.

TABLE 2. Maximum voluntary isometric force (strength) exerted by the knee extensor muscles and muscle cross-sectional area determined for male and female subjects

| | Males | | | Females | | |
|---|---|---|---|---|---|---|
| | Mean | S.D. | Range | Mean | S.D. | Range |
| Force at ankle, $F_s$ (N) | 783 | 118 | 543–1024 | 493 | 65 | 368–631 |
| $F_s$/Body weight (N/kg) | 11·03 | 1·82 | 8·00–14·38 | 8·42 | 1·59 | 5·86–11·56 |
| $F_s$/Lean body mass (N/kg) | 13·28 | 1·83 | 9·77–16·28 | 11·53 | 1·96 | 8·24–15·17 |
| Muscle cross-sectional area (cm$^2$) | 83·2 | 12·3 | 59·7–106·4 | 55·4 | 6·2 | 45·10–64·2 |
| $F_s$/cross-sectional area (N/cm$^2$) | 9·49 | 1·34 | 7·07–12·55 | 8·92 | 1·11 | 6·63–11·01 |

Differences between the male and female groups were assessed for statistical significance by use of Student's *t* test for unpaired data. Linear regression coefficients ($r$) were calculated using the method of least squares.

## RESULTS

The male subjects were taller ($P < 0{\cdot}001$), heavier ($P < 0{\cdot}001$) and had a lower body fat content ($P < 0{\cdot}001$) than the female subjects. All calculations of muscle strength were based on the stronger of the two legs for each individual; in twenty-two of the male subjects and twenty-one of the female subjects, this was the right leg. As might be expected, the male subjects were significantly stronger ($P < 0{\cdot}001$) than the females (Table 2). If a correction is made for the body weight the strength of the male subjects was still greater than that of the females ($P < 0{\cdot}001$). This difference is due at least in part to the higher body fat content of the females, since adipose tissue can make no contribution to strength. However, even if strength is expressed in terms of lean body mass, the males were still stronger than the females ($P < 0{\cdot}005$).

As the males and females represent distinct populations, the relationships between strength and body weight have been calculated separately (Figs. 2 and 3). There is no significant relationship between strength and body weight for the male subjects ($r = 0{\cdot}32$; $P > 0{\cdot}05$) but there is a significant correlation between strength and lean body mass for the same subjects ($r = 0{\cdot}50$; $P < 0{\cdot}01$). No significant correlation was found to exist between strength and body weight for the female subjects ($r = 0{\cdot}09$;

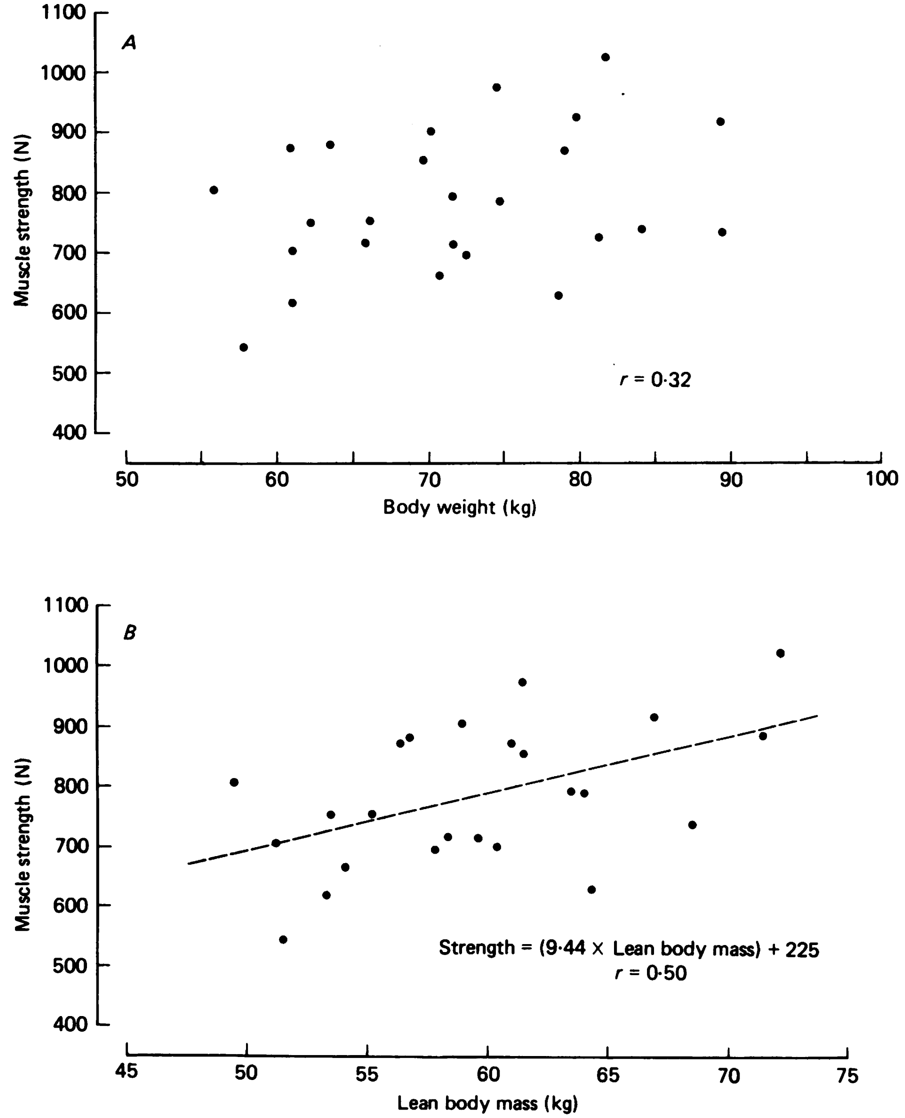

Fig. 2. *A*, the relationship between muscle strength and body weight for male subjects ($n = 25$). *B*, the relationship between strength and lean body mass for the same subjects. One subject has been excluded from this Figure as it proved impossible to obtain an accurate assessment of body fat content.

$P > 0{\cdot}05$), but in this case no significant relationship was observed between strength and lean body mass ($r = 0{\cdot}19$; $P > 0{\cdot}05$).

The values obtained for muscle cross-sectional area are presented in Table 2. Muscle cross-sectional area of the male subjects was greater ($P < 0{\cdot}001$) than that of the female subjects. Once again the male and female subjects clearly belong to separate populations as the muscles of the female subjects are both smaller and weaker than those of the males. Regression analysis of the data for male subjects revealed a

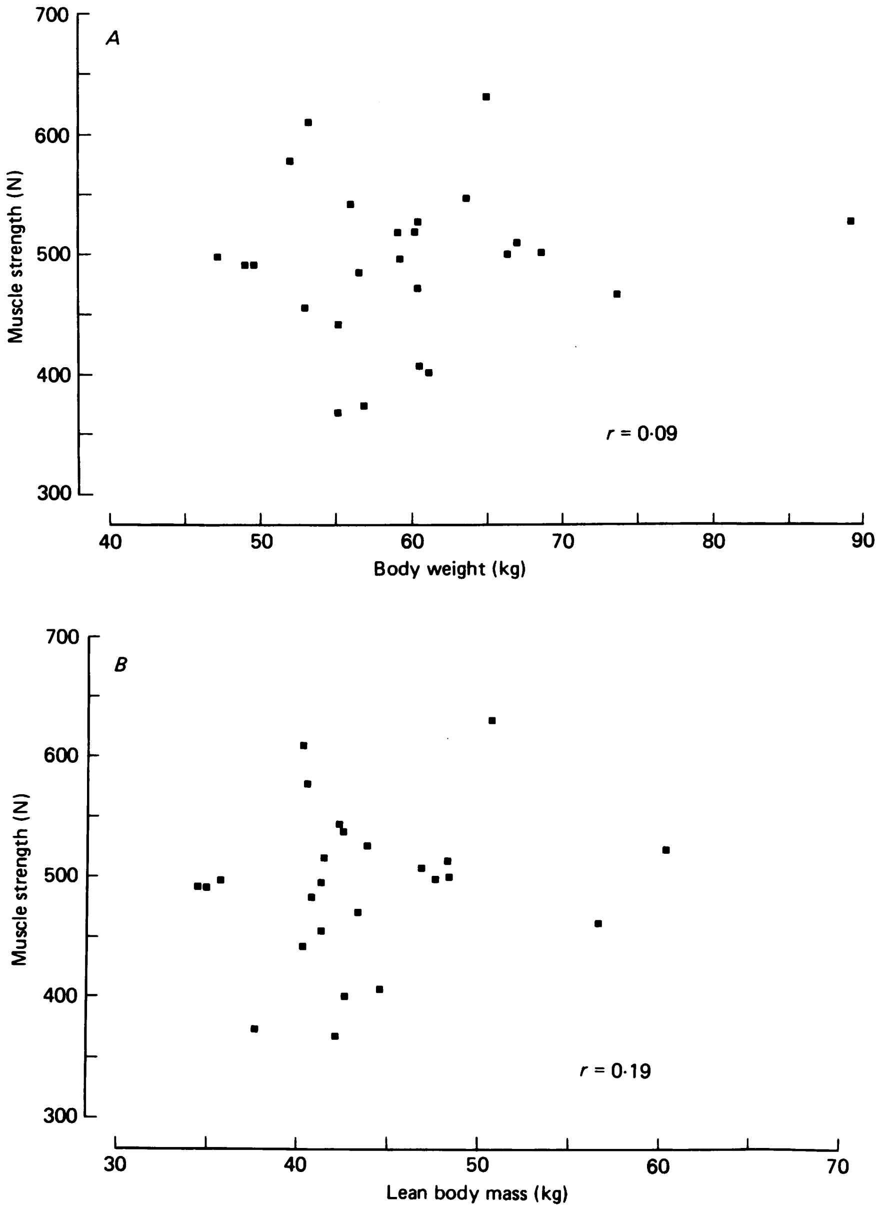

Fig. 3. *A*, the relationship between muscle strength and body weight for female subjects ($n = 25$). *B*, the relationship between strength and lean body mass for the same subjects.

significant ($r = 0{\cdot}59$; $P < 0{\cdot}01$) relationship between strength and muscle cross-sectional area (Fig. 4). A similar analysis performed on the data obtained from female subjects again showed a significant ($r = 0{\cdot}51$; $P < 0{\cdot}01$) relationship between strength and muscle cross-sectional area (Fig. 5). The ratio of strength to cross-sectional area for the male subjects was greater, but not significantly so, than that for the female subjects (Table 2).

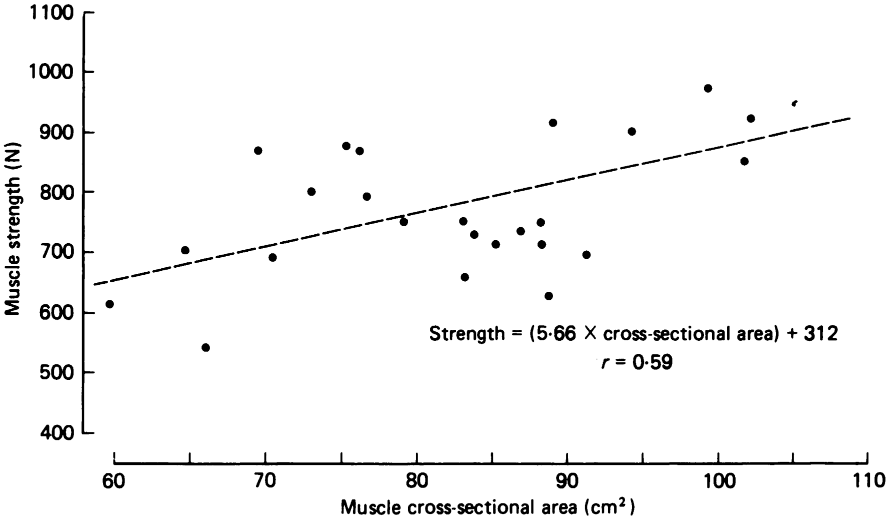

Fig. 4. The relationship between strength and cross-sectional area of the knee extensor muscles for male subjects.

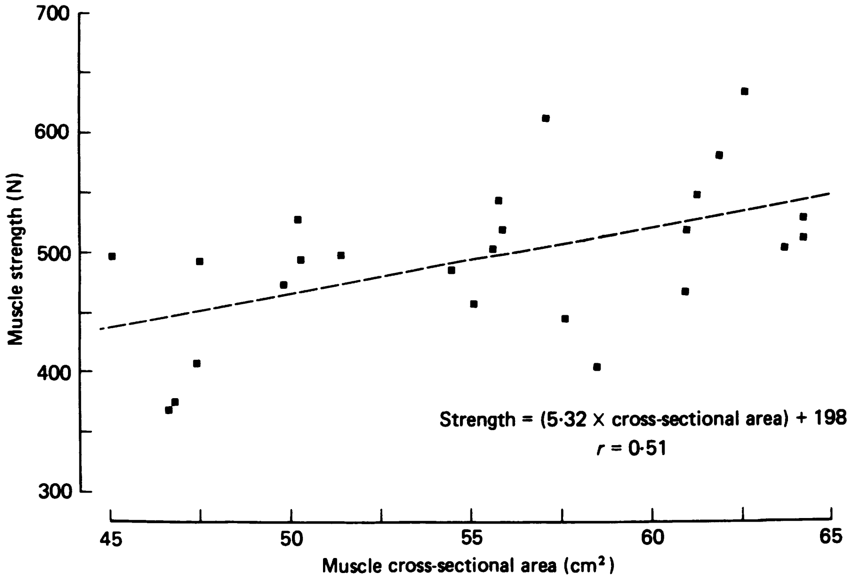

Fig. 5. The relationship between strength and cross-sectional area of the knee extensor muscles for female subjects.

## DISCUSSION

### *Strength and body weight*

Male subjects studied in the present investigation were able to exert a force with the knee extensor muscles of their stronger leg equivalent to 1·12 times body weight. Female subjects could exert a force of 0·86 times body weight. These values are somewhat higher than those reported by Edwards *et al.* (1977) using an almost identical apparatus to measure strength; they found that normal adult subjects could exert a force of about 75% of body weight. Tesch & Karlsson (1978) however, again using a similar apparatus, reported values higher than those obtained in the present study.

No significant correlation was found to exist between strength and body weight for male or for female subjects. Both Edwards *et al.* (1977) and Young *et al.* (1981) have reported that a significant relationship between these variables does exist. In both of these studies, however, results obtained from male and female subjects have been included together in the statistical analysis. It is clear from the results of the present study, and was reported by Young *et al.* (1981) that male subjects are stronger for their weight than females. This being the case, it is not valid to include data obtained from both sexes in the same analysis. The lack of a positive relationship between strength and body weight is surprising in view of the fact that the quadriceps is a weight-bearing group of muscles; the training stimulus to which it is exposed as a result of normal daily activity might be expected to depend upon the individual's body weight.

It seems possible that the apparent lack of any relationship between strength and body weight may be due to the varying degrees of fatness of the subjects studied, since adipose tissue cannot contribute to the generation of force. This would appear to be true for the male subjects since there is a significant positive correlation between strength and lean body mass; no such relationship was found to exist for the female subjects.

### *Strength and muscle cross-sectional area*

The cross-sectional area of the quadriceps muscle as measured in the present study is comparable with results obtained by Bulcke *et al.* (1979) for normal male and female subjects in the same age group.

Although we have found a positive significant correlation between strength and cross-sectional area for both male and female subjects, there is nonetheless considerable variability between individuals, and also a tendency for males to have a higher ratio of strength to cross-sectional area than females, although this difference is not statistically significant. This latter observation is in agreement with a report by Morris (1948) that the muscular strength of females, after correction for differences in cross-sectional area, is approximately 80% of that of males. The present results indicate almost a two-fold difference between this ratio for the weakest female (6·63) and the strongest male (12·55) and an explanation for this difference must be sought.

### *Anatomical considerations*

*Muscular.* The muscle image obtained by computed tomography scanning as conducted in the present study measures the anatomical cross-section of the muscle at right angles to its long axis. In none of the four individual muscles which comprise the quadriceps group, however, do the individual muscle fibres run parallel to each other along the long axis of the muscle. If the strength of a muscle is to be propertly related to its cross-sectional area, the cross-section should be measured at a right angle to the muscle fibres. Thus for the three vasti, the physiological cross-section of each muscle lies at an angle to its anatomical cross-section (Haxton, 1944). Determination of the physiological cross-sectional area of m. rectus femoris is further complicated by its bipennate structure (Williams & Warwick, 1980). There is no satisfactory method of determining the physiological cross-section of pennate muscles in the intact individual. Haxton (1944), however, reported that the angle between the muscle fibres and the tendon of insertion in post mortem specimens of gastrocnemius and soleus was fairly constant. If this observation holds true for the quadriceps muscles then variations in muscular architecture are unlikely to account for the variability in the ratio of strength to cross-sectional area.

Alexander & Vernon (1975) reported that the angle of pennation for all four muscles in the knee extensor group was approximately the same, varying from 13–18°, although these data were obtained from a single cadaver only. The errors which can arise from extrapolation to living subjects of data obtained from post-mortem material are illustrated by the fact that the calculated physiological cross-sectional area of the quadriceps for this specimen (body weight 64 kg) was 135 $cm^2$; this seems rather large compared with the values for anatomical cross-sectional area of this muscle group obtained in the present study (60–106 $cm^2$).

If the total number of fibres in the muscle is constant, the angle of pennation is dependent in part upon the size of the individual muscle fibres. Muscular hypertrophy, resulting from an increased cross-sectional area of the component fibres, results in an increased angle of pennation (Gollnick, Timson, Moore & Riedy, 1981). This being the case, hypertrophy will cause a decrease in the ratio of strength to anatomical cross-sectional area if the stress which can be developed within the fibres remains constant. This hypothesis, derived theoretically by Alexander & Vernon in 1975, is confirmed by the present data; a significant inverse relationship exists between muscle cross-sectional area and the ratio of strength to cross-sectional area for both male ($P < 0{\cdot}005$) and female ($P < 0{\cdot}05$) subjects.

Although the clarity of the image produced by computed tomography is such that it is easy to distinguish between subcutaneous fat and muscle tissue, measurement of total muscle cross-sectional area takes no account of the composition of the muscle. Since the force of contraction of the muscle might be expected to be related to the cross-sectional area of the contractile apparatus, replacement of muscle protein with fat or fluid could be a source of error in the present study. An added advantage of the use of computed tomography rather than ultrasonography in determination of muscle size is that it is possible to obtain a qualitative assessment of muscle composition; the image density, a measure of the X-ray attenuation coefficient of a tissue, measured in Hounsfield Units (HU), is $-106$ HU for fat and $+54$ HU for normal muscle (Brenton, Edwards, Grindrod & Tofts, 1981). The variation in muscle density between subjects in the present study was small, however, and correction of the measured muscle cross-sectional area for the area occupied by fat, as estimated from the mean Hounsfield number for the whole muscle area, had no significant effect on the results.

Normal human skeletal muscle is composed of variable proportions of two major types of muscle fibres having different contractile and biochemical characteristics (Brooke & Kaiser, 1970). Type I fibres have been shown to predominate in athletes engaged in endurance events, and Type II fibres in individuals engaged in events requiring speed and strength (Saltin, Henriksson, Nygaard, Andersen & Jansson, 1977). Thorstensson (1976), reported that the maximum isometric force which could be exerted by the knee extensor muscles was unrelated to the proportions of the different fibre types in m. vastus lateralis. In contrast to these results, Tesch & Karlsson (1978) found a significant positive correlation between the strength of the knee extensor muscles and the percentage of Type II muscle fibres in m. vastus lateralis. These studies must be interpreted with caution, as no measurements of muscle cross-sectional area were made. The results of Tesch & Karlsson (1978) were reported to indicate that the intrinsic strength of Type II muscle fibres is greater than that of Type I fibres. This is true only if the muscles studied had a comparable cross-sectional area.

Studies on animal muscle have suggested that the maximum isometric stress which can be developed by muscle is independent of the proportions of Type I and Type II fibres present (Close, 1972). Burke & Edgerton (1975), however, reported that muscles with a high proportion of Type II fibres could exert a greater isometric tension than muscles composed mainly of Type I fibres.

Muscle fibre type distribution was not measured in the subjects used in the present study, but in view of the conflicting results reported in the literature, variations in the muscle fibre type composition must be considered as a possible explanation for the variation in muscle strength per unit cross-sectional area.

*Skeletal.* For the purpose of this study, the force exerted at a level approximately 2 cm above the malleoli has been taken to represent the strength of the muscles involved in the contraction. The absolute force generated by the muscles is greater than the measured force due to the unfavourable mechanical advantage of the system (Fig. 6). At equilibrium (during an isometric contraction) the clockwise moments about the fulcrum located in the joint must equal the anticlockwise moments i.e.

$$F_Q \, . \, R_Q = F_S \, . \, R_S,$$

where: $F_Q$, force developed in quadriceps tendon; $F_S$, force measured at level of ankle; $R_Q$, perpendicular distance between line of action of force developed by quadriceps and the centre of rotation (fulcrum) and $R_S$, perpendicular distance between line of action of force at ankle and fulcrum.

Hence, $$F_Q = F_S \, . \, (R_S/R_Q).$$

Calculation of the absolute force exerted by the muscles through their tendons therefore demands a knowledge of the dimensions of the levers involved.

Morris (1948) and Ikai & Fukunaga (1968) have used X-ray photographs to determine the point of insertion of the muscle under study onto the bone and also to identify the anatomical location of the fulcrum. Haxton (1944) used limbs from cadavers to measure the ratio between the tension in the tendo calcaneus and the pressure on the ball of the foot in his study of the strength of ankle flexors. In all of these reports, variations between individuals in the mechanical advantage of the levers involved were small, leading to the conclusion that differences in this respect are unlikely to have a significant influence on the present results.

If the knee joint is bent at an angle of 90° as in the present study, the moment arm of the quadriceps ($R_Q$) is approximately 3·7 cm (Lindahl & Movin, 1967; Smidt, 1973). Mean lower leg length, from the head of the fibula to the lateral malleolus (approximately $R_S$ was 40·2 ± 1·9 cm (mean ± S.D.) for the male subjects and 38·0 ± 2·3 cm for the female subjects in the present study. The range was 36·7–43·5 cm for males and 33·5–42·2 cm for females. The force developed in the patellar tendon must therefore be approximately 10 times greater than that produced at the site of measurement. In spite of the evidence which suggests that variability in this ratio between individuals is small, it seems probable that small differences between subjects in the location of the centre of rotation of the joint or in the dimensions of the lower limbs will contribute to the observed variability in the ratio of muscle strength to cross-sectional area.

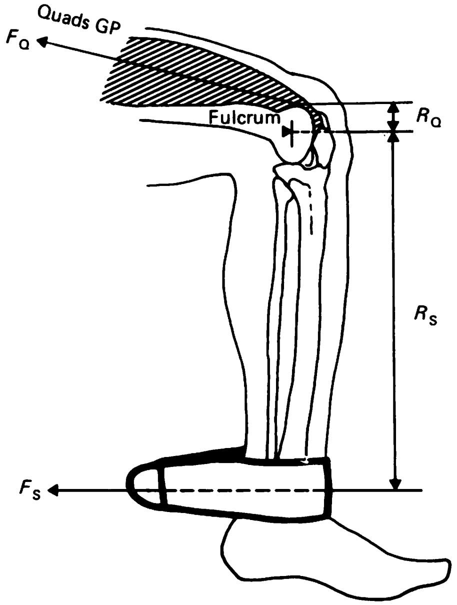

Fig. 6. Diagrammatic representation of skeletal structures associated with the knee joint. The exact anatomical position of the centre of rotation can be established by construction of a two-dimensional bone model based on an X-ray of each individual joint. Precise location is essential, as small (5–10 mm) errors will result in large changes in the ratio $\bar{R}_S/\bar{R}_Q$. A full explanation is given in the text.

The measured force will also depend upon the angle at which the knee joint is bent since this will influence the contractile characteristics of the muscle by changing the length of the muscle and the angle of pennation and will also alter the length of the moment arm of the quadriceps. Lindahl, Movin & Ringqvist (1969) have shown that the maximum force is developed at an angle of 105–120°. The strength measured in the present study is thus less than the maximum which the muscle is capable of developing.

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A
B
ARB ROI
AREA 10243
AVR 63.0
STD 11.8

## EXPLANATION OF PLATE

Images obtained from computerised axial tomographic scans of two subjects performed at the mid-thigh level. *A*, female subject (body fat content = 33 %). *B*, male subject. The knee extensor muscles have been outlined: the area under the curve is shown in mm$^2$. AVR refers to the average density (in HU) of the pixels within this area, with the S.D. of the density measurements also indicated (STD).