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PATELLAR FORCES DURING KNEE EXTENSION

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ABSTRACT. A radiographical study of 20 loaded knees of healthy subjects and a knee dissection study of 20 specimens were performed in order to present a two-dimensional patello-femoral joint biomechanical model. A constant knee-extending moment gave 25–40 % lower force magnitudes in the patellar tendon than in the quadriceps tendon if the knee was flexed to 60–120 deg. The magnitude of the patello-femoral joint compressive force reached its maximum at 90 deg knee angle and decreased slightly towards 120 deg. A compressive force between quadriceps tendon and femoral intercondylar groove was present above 60 deg knee angle and its magnitude was estimated. The patellar forces in women were about 20 % higher than in men. The biomechanical model may be used in knee rehabilitation activities to optimize and individualize exercise programmes. The model may also be applied to daily activities in order to quantify patellar forces.

Key words: biomechanics, joint load, models biological, orthopaedic surgery, patello-femoral joint

Patello-femoral pain is a common clinical symptom. It is important to learn the specific pathology causing the pain in order to find the optimal treatment and to improve the chances of obtaining good results from the therapy. At the same time, knowledge of the biomechanical behaviour of the patello-femoral joint is a prerequisite for understanding the pathological behaviour of the joint. Chondromalacia patellae is one defined pathological condition that gives rise to patello-femoral pain and this disease has been extensively studied (1, 15, 17, 27). The cause of chondromalacia patellae is not known, but high patello-femoral stresses are mentioned as one aetiological factor, among others. It is well-known from clinical practice that patients with patello-femoral osteoarthrosis experience knee pain when high stresses are put on the patello-femoral joint, for example when climbing stairs. Quadriceps muscle exercises are often used in the treatment of patients with patello-femoral pain. It is considered important to avoid high forces in or close to the joint in order to spare injured or weak structures. For these reasons, it is necessary for the therapist to have a good understanding of the biomechanics of the knee joint and the magnitude of the forces arising in and around it during knee exercises (18, 20, 28, 32).

Reilly & Martens (29) estimated the magnitude of the patello-femoral joint compressive force (Fcp) during various activities. They calculated Fcp to be 0.5 times body weight (bw) during level walking and 3.3 bw during stair-climbing. Smidt (31) calculated Fcp during maximum knee extension and found mean values between 0.79 and 2.64 bw, depending on the knee angle. Matthews et al. (24) suggested a linear relationship between knee angle and patellar mechanism angle (corresponding to ψ in the present study, Fig. 1) in order to better quantify Fcp at various knee angles. Dahlqvist et al. (8) estimated Fcp during squatting and rising from a deep squat and found maximum Fcp values between 4600 N and 5900 N or about 7 times bw. Seedhom & Terayama (30) calculated Fcp to be 2.4 bw during rising from a chair without the aid of the arms and 0.7 bw with arm support. Ellis et al. (11) also studied knee joint forces during rising from seated positions, finding a maximum Fcp between 2 and 6 bw. In a later study, Ellis et al. (13) showed that the magnitude of Fcp is 5 bw during rising from a normal chair, 4.5 bw from a higher chair, and 4.2 bw with the aid of the arms.

In most patello-femoral biomechanical models, the forces in supra- and infrapatellar tendons have been considered to be of the same magnitude (4, 14, 18, 20, 24, 29, 31). However, as early as in the 1940's, Haxton (19) showed for the flexed knee joint that the forces in the supra- and infrapatellar tendons are not of the same magnitude, the quadriceps tendon taking up higher forces than the patellar tendon. In recent years several authors have noted a similar kind of relation between the tendons (5, 6, 12, 23).

Ahmed et al. (2) showed that the experimentally measured patello-femoral compressive force is low-

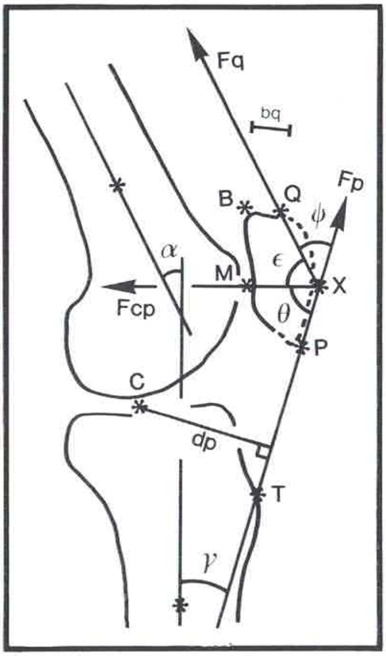

Fig. 1. Forces, angles, distances and bony landmarks at 30 deg knee angle (α). The force in the patellar tendon (Fp) passes through the midpoints of the tendon at tibial tuberosity (T) and patellar apex (P). The compressive force in the patello-femoral joint (Fcp) is projected through the centre of the contact point (M). For explanation of other symbols, see nomenclature and the text.

er and had a different pattern at various knee angles than that found using various theoretical patello-femoral biomechanical models. This inconsistency indicates a need for a better theoretical patello-femoral biomechanical model than those presented earlier.

The purpose of the present investigation was to develop a two-dimensional biomechanical model of the human patello-femoral joint in order to quantify the compressive forces arising in and around the joint during various knee extending activities. The model was based on a knee morphological study using specimens and an X-ray study of a loaded knee using healthy subjects. The quantitative morphological and anatomical data are also presented in this study. The following more specific questions were analysed:

1. What is the dimensional difference between the patellar (infrapatellar) and the quadriceps (suprapatellar) tendons?
2. What is the magnitude of the angles between the forces in the patellar tendon, the quadriceps tendon, and the patello-femoral joint?
3. What, at various knee angles and load moments, is the magnitude of these tendon and joint compressive forces?
4. What is the magnitude of the compressive force between the quadriceps tendon and the femoral intercondylar groove?
5. What is the ratio between patellar and quadriceps tendon forces at various knee angles?
6. Are there any differences between the sexes in these respects?
7. What practical implications may be found concerning the knowledge of how forces act in and around the patello-femoral joint?

MATERIALS AND METHODS

Autopsy

Human knees of autopsy specimens were used in order to determine the location of the patellar and quadriceps tendon insertion on the patella. The left knee joints of 11 men and 13 women were dissected, but the knees of one man and 3 women were excluded from the study due to osteoarthrosis in the patello-femoral joint. Thus, 10 knees of each sex were accepted for the dissection study. The patella was cut off from the extensor apparatus at the patellar base through the quadriceps muscle (suprapatellar) tendon and at the apex through the patellar (infrapatellar) tendon. The thickness and breadth of the patellar and quadriceps tendons were measured at the insertion on the patella. The patellar tendon insertion length on the tibial tuberosity was measured, and also the length and breadth of the patella.

X-ray

Twenty healthy subjects (10 men and 10 women) were selected for the study. No subject exhibited any knee pathology and none had earlier undergone any kind of knee surgery. Lateral X-ray films were taken of the left knee at five knee angles; straight knee (zero deg) and 30, 60, 90, and 120 deg knee flexion angle. One X-ray film was also taken in the frontal plane with the knee straight. All the X-ray pictures were taken with the subjects standing, and in this way the knee was loaded.

For the straight knee pictures, the subject was asked to extend the knee in order to contract the quadriceps muscle. However, the X-ray films showed that not all subjects activated their knee extensor at this particular moment (patellar tendon not tensed, patella position accordingly too low). The biomechanical situation that arose here could not be exploited due to lack of contact bewteen patella and femur. For this reason the number of subjects was lower, $n=7$ (women) and $n=8$ (men), for the straight knee X-ray data. The film–focus distance was 155 cm and the distance between knee joint centre and film was 15 cm. The enlargement factor was calculated to 1.11 (155/140), and all X-ray data have been corrected for this magnification. X-ray films of size 30×40 cm were used.

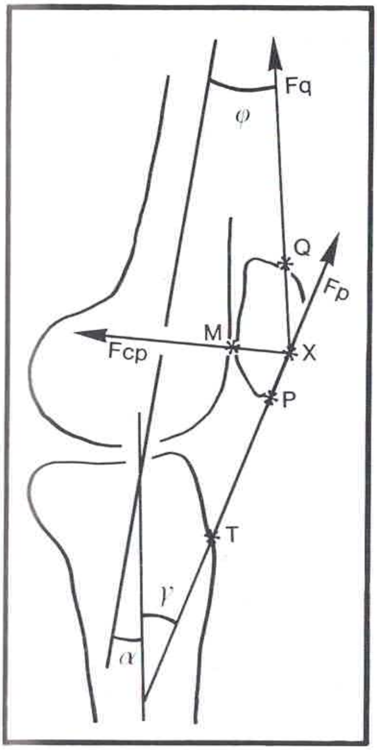

Fig. 2. Forces, angles and bony landmarks at the straight knee. The quadriceps tendon force (Fq) passes through the quadriceps tendon midpoint (Q) and does not run parallel to the long axis of femur, giving rise to the φ angle. For explanation of other symbols, see nomenclature and the text.

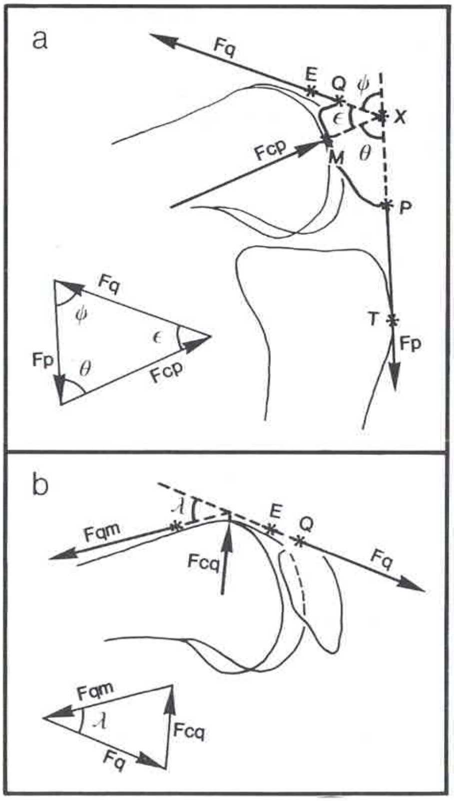

Fig. 3. (*a*) Free body diagram of patella at 120 deg knee angle. The patello-femoral compressive force (Fcp) equals the vector sum of the patellar tendon force (Fp) and quadriceps tendon force (Fq) and falls through the midpoint (M) of the patello-femoral contact, perpendicularly to the joint surface. (*b*) Free body diagram of distal part of quadriceps tendon. The compressive force between quadriceps tendon and intercondylar groove (Fcq) equals the vector sum of Fq and proximal part of quadriceps tendon force (Fqm). For explanation of other symbols, see nomenclature and the text.

Forces

Fig. 1. shows that the force in the patellar tendon (Fp) passes through the midpoints of the tendon at tibial tuberosity (T) and patellar apex (P) (26). The compressive force in the patello-femoral joint (Fcp) was projected through the centre of the contact point (M), perpendicular to the joint surface. The force in the quadriceps tendon (Fq) was assumed to run parallel to the long axis of femur at angles 30 deg and 60 deg. Fq passes through the midpoint of the quadriceps tendon insertion at the patellar base (point Q). To find point Q on the X-rays the proximal, dorsal bony corner of the patellar base (point B) was identified. The distance between these two points, bq-distance, was estimated in the morphological study and its mean value was used on the X-ray films. Fq does not run parallel to the long axis of femur at the straight knee (Fig. 2). In this joint position the direction of Fq was determined as the line between the Fp–Fcp intersection (point X) and the midpoint of the quadriceps tendon (point Q) at the patellar base.

At knee angles 90 deg and 120 deg the quadriceps tendon was curved in the femoral intercondylar groove. The magnitude of the force in the proximal part of the quadriceps muscle (Fqm), (Fig. 3 *b*) was considered to be the same as in the distal part (Fq). The acute angle between these two forces is termed the λ angle. It gave rise to a force between the distal part of the quadriceps tendon and femoral intercondylar groove (Fcq), (Fig. 3 *b*). At knee angles above 60 deg the direction of Fq was estimated as the line between points E and Q. Point E was localized on the X-ray films as the midpoint of the quadriceps tendon 15 mm proximal to the patellar base.

There are many force vectors (force directions and magnitudes) acting on the bone by one particular tendon. All biomechanical models use approximations and in this study the forces in the various parts of the tendon were presumed to act as one total single force vector from tendon midpoint at one place to tendon midpoint at the other. This assumption is fair enough for straight tendons, but at knee angles of 90 deg or more where the quadriceps tendon is no longer straight, an extra point (E), (Fig. 3) has been used.

Angles

The angles show the following relations:

$\psi+\varepsilon+\theta=180$ degrees (deg)

$\psi=\alpha+\gamma+(\varphi)-(\lambda)$

Regarding explanation of angles, see nomenclature and Figs. 1–3. The knee angle (α) was zero when the knee was straight. An overextension of the knee joint gave a negative value of α. Angle φ was present only over the last few degrees of knee extension and λ only when the knee was flexed to more than 60 deg.

Statistics

ANOVA 3-way variance-analysis, Student's paired and unpaired *t*-tests were the statistical tests used. The statistical significance levels chosen were consistently $p<0.01$.

Nomenclature

Me = Extending knee muscular moment about point C
Mf = Flexing knee load moment about point C

Fp = Force in patellar tendon
Fcp = Compressive force in the patello-femoral joint
Fq = Force in quadriceps tendon, distal part
Fqm = Force in quadriceps tendon, proximal part
Fcq = Compressive force between quadriceps tendon and femoral intercondylar groove.

α (alpha) = Knee angle (straight knee is defined as 0 deg)
γ (gamma) = Angle between Fp and long axis of tibia
ε (epsilon) = Angle between Fcp and Fq
ψ (psi) = Angle between tween Fp and Fq
θ (theta) = Angle between Fp and Fcp
φ (fi) = Angle between Fq and long axis of femur
λ (lambda) = Angle between Fq and Fqm

A = Apex patellae
B = Bony landmark at dorsal corner of patellar base
C = Centre of contact pressure point between tibia and femur
E = Midpoint of quadriceps tendon 15 mm proximal to patellar base
M = Centre of contact pressure point between patella and femur
P = Midpoint of patellar tendon at apex patellae
Q = Midpoint of quadriceps tendon at insertion of patellar base
T = Midpoint of patellar tendon at tuberositas tibiae
X = Intersection point of Fp, Fq and Fcp.

bq = Distance between points B and Q
dp = Moment arm of Fp to point C.

Biomechanical analysis

Presuming that static equilibrium prevails, the sums of forces and moments are zero. The tension in the patellar tendon, Fp, may be calculated from the equation:

$$\mathrm{Fp}=\mathrm{Me}/\mathrm{dp} \qquad (1)$$

where dp is the moment arm or the perpendicular distance from Fp to the contact point between tibial and femoral condyles (point C, Fig. 1). The location of C and the length of the moment arm at various knee angles have been given elsewhere (26). The magnitude of the flexing knee load moment about C (Mf) can be determined if the magnitude and direction of the external forces acting on the tibia are known. Me is the extending knee muscular moment about C and in a static situation it equals Mf.

Three forces act on the patella. If we consider the patella in a free body diagram (Fig. 3 *a*) we get the vector equation:

$$\bar{\mathrm{F}}\mathrm{p}+\bar{\mathrm{F}}\mathrm{q}+\bar{\mathrm{F}}\mathrm{cp}=\bar{0} \qquad (2)$$

From elementary trigonometry we know that:

$$\mathrm{Fcp}=\mathrm{Fp}\,(\sin\psi)/(\sin\varepsilon) \qquad (3)$$

Insertion of equation (1) gives:

$$\mathrm{Fcp}=\mathrm{Me}/\mathrm{dp}\,(\sin\psi)/(\sin\varepsilon) \qquad (4)$$

Projecting the vectors $\bar{\mathrm{F}}\mathrm{cp}$ and $\bar{\mathrm{F}}\mathrm{p}$ on $\bar{\mathrm{F}}\mathrm{q}$ gives the magnitude of Fq:

$$\mathrm{Fq}=\mathrm{Fcp}\,(\cos\varepsilon)+\mathrm{Fp}\,(\cos\psi) \qquad (5)$$

Equations (1), (4) and (5) give:

$$\mathrm{Fq}=\mathrm{Me}/\mathrm{dp}\,(\sin\psi)/(\sin\varepsilon)+\mathrm{Me}/\mathrm{dp}\,(\cos\psi) \qquad (6)$$

Considering the distal part of the quadriceps tendon in a free body diagram (fig. 3 b) we get the vector equation:

$$\bar{\mathrm{F}}\mathrm{q}+\bar{\mathrm{F}}\mathrm{qm}+\bar{\mathrm{F}}\mathrm{cq}=\bar{0} \qquad (7)$$

As forces Fq and Fqm are assumed to have the same magnitude we get from equation (7):

$$\mathrm{Fcq}=2\,\mathrm{Fq}\,(\sin\lambda/2) \qquad (8)$$

Equations (6) and (8) give:

$$\mathrm{Fcq}=2\,(\sin\lambda/2)\,\mathrm{Me}/\mathrm{dp}\,(\sin\psi)\,(\cos\varepsilon)/(\sin\varepsilon)+\mathrm{Me}/\mathrm{dp}\,(\cos\psi) \qquad (9)$$

Consequently, the magnitude of forces Fp, Fq, Fcp, and Fcq may be determined at various knee angles (α) and flexing load moments (Mf) if the angles (ψ, ε, and λ) between the forces are known.

RESULTS

Table I shows the morphological patellar and quadriceps tendon data from the dissected specimens. The patellar tendon was 25–30% thinner and narrower than the quadriceps tendon. Men had significantly thicker and wider tendons than women.

In fig. 4 the mean magnitudes of ψ, ε and θ angles are shown at various knee angles. The same changing patterns of these angles were seen for women (Fig. 4 *a*) and for men (Fig. 4 *b*). Angle ψ increased from about 20 deg at the straight knee to about 65

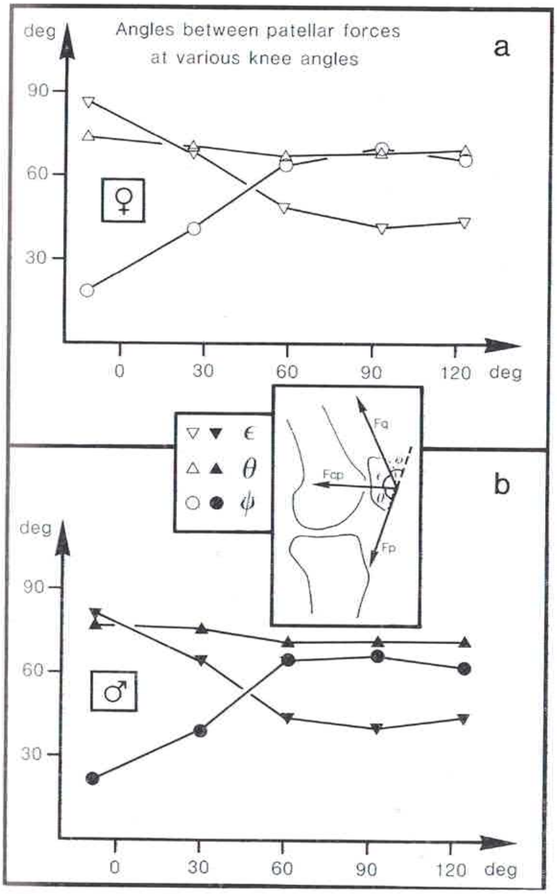

Fig. 4. Mean magnitudes of angles, ε, θ and ψ for women and men at various knee angles (x-axis). No statistically significant difference between women (above) and men (below). SD of the mean ranges between 2–14 deg.

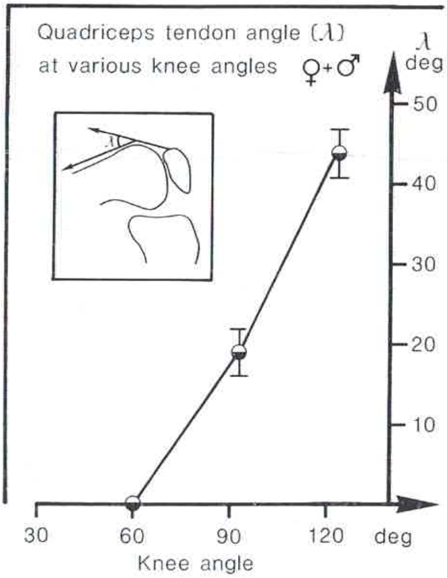

Fig. 5. Angle λ at various knee angles (x-axis) for men and women together. No statistically significant difference between the sexes. The 95% confidence intervals of the mean are drawn.

deg at knee angles of 60–120 deg. The higher the value of ψ the higher the patello-femoral joint compressive force became (see eq. (3)). Note that ψ reached its maximum at 90 deg. Angles ε and θ showed an obvious and statistically significant difference at knee angles of 60–120 deg, where θ was higher (mean 67–73 deg) than ε (mean 41–49 deg). This difference was not seen at straighter knee angles. Thus, the patello-femoral joint compressive force for both sexes did not divide the angles between patellar and quadriceps tendons into two equal parts when the knee was flexed to 60 deg or more. The implications of this fact will be further analysed under Discussion.

Angle φ (Fig. 2) was only present in the straight knee. Its magnitude was somewhat higher for men (mean 12.3 deg, SD=5.9) than for women (mean 7.1 deg, SD=4.1) but the difference was not statistically significant. The presence of φ indicates that there is a patello-femoral joint compressive force also in the straight knee. At knee angles of 90 deg and more the quadriceps tendon curves along the femoral intercondylar groove. Fig. 5 shows the magnitude of this angle of curve (λ) at 90 and 120 deg knee angle. At straighter knee angles, λ was not present (λ = zero).

If the magnitudes of the knee extending moment and knee angle are known the forces may be calculated in the patellar tendon (Fp), quadriceps tendon (Fq), patello-femoral joint (Fcp), and

Table I. *Morphological and anatomical data of the dissected specimens*

Distances in mm. SD in parentheses

Variable	Women, n=10	Men, n=10
Quadriceps tendon thickness	6.4 (1.1)	7.4 (1.5)
Quadriceps tendon breadth	47.4 (1.8)	50.0 (4.8)
Patellar tendon thickness	4.5 (0.8)	5.6 (1.0)
Patellar tendon breadth	33.8 (1.9)	35.8 (2.2)
Distance bq (see Fig. 1)	10.7 (1.4)	12.3 (1.4)
Femurepicondyle breadth estimated with callipers	84.4 (3.6)	93.7 (4.7)
Patellar breadth	45.4 (3.9)	49.5 (4.0)
Patellar height	43.6 (3.1)	48.2 (2.8)

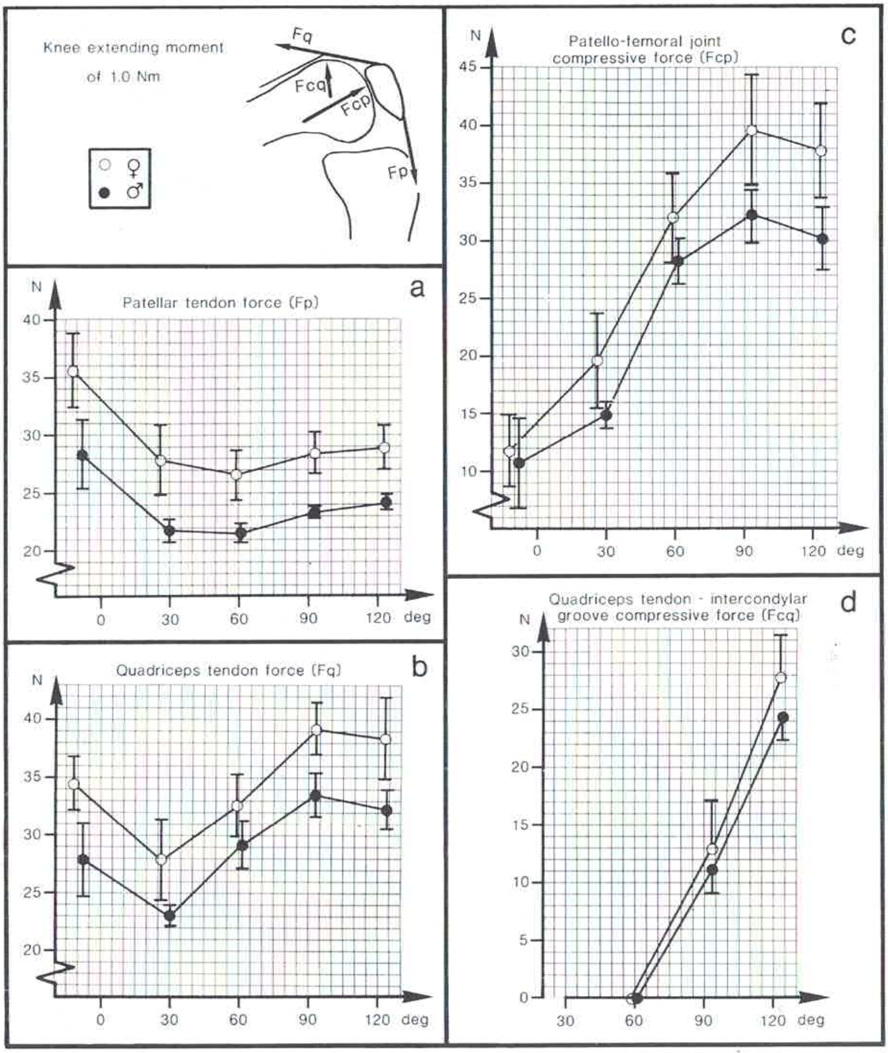

Fig. 6. Magnitude of tendon and compressive forces (*y*-axes) at various knee angles (*x*-axes). The knee-extending moment is 1.0 Nm. *Upper curve:* women; *lower curve:* men. The 95% confidence intervals of the means are drawn.

between the quadriceps tendon and the femoral intercondylar groove (Fcq). In Fig. 6 the extending knee moment was 1.0 Nm. Fp had its maximum magnitude at the straight knee and its minimum at 60 deg knee angle. Fq reached its maximum at 90 deg knee angle and its minimum at 30 deg. It can be seen that Fp was lower than Fq when the knee was flexed to 60 deg or more. At straighter knee angles, Fq and Fp were almost equal. Fcp reached its maximum at 90 deg knee angle, and between 60 deg and 120 deg its magnitude was almost the same as for Fq. Fcp was lowest at the straight knee but it was not zero. At straighter knee angles Fcp was less than Fq and Fp. Fcq is a function of angle and Fq (equation (9) and was present above 60 deg knee flexion angle. The magnitude of Fcq increased almost linearly with increasing knee angle. Regarding all forces, the same pattern was seen for men and women but the force magnitudes of women were consistently about 20% higher than for men. The sex difference was statistically significant for Fp, Fq and Fcp but not for Fcq.

The forces in the quadriceps and patellar tendons were not equal for all knee angles. The relation

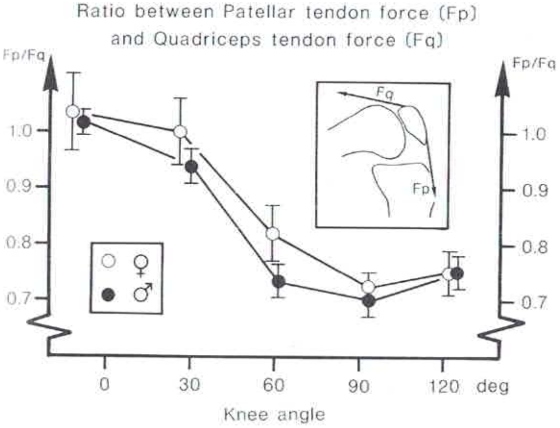

Fig. 7. Ratio Fp/Fq (*y*-axis) for men and women at the various knee angles (*x*-axis). The 95% confidence intervals of the means are drawn. No statistically significant difference between the sexes. Ratios at straight knee and at 30 deg knee flexion angle are statistically different from the other ratios at 60 deg or more.

between Fp and Fq is shown in Fig. 7. The ratio was around 0.70–0.80 at knee angles of 60–120 deg, implying that the force in the patellar tendon was lower than that in the quadriceps tendon. In straighter knee joint positions, the ratio was close to 1.0, i.e. the tendon forces were of the same magnitude. The main change in this ratio occurred between knee angles 30 deg and 60 deg.

DISCUSSION

The biomechanical model was made possible by using measurements both from autopsy specimen knees and from knee X-ray films of healthy young subjects. The anthropometrical knee data of these two groups were in good agreement with each other (Tables I, II). Tendon thickness and the location of tendon insertion did not change much between subjects (SD for the variables is low). The two groups of subjects were of different age but anatomical sizes of bones and tendons are quite constant during aging. Therefore quantitative data from the morphological investigation may be properly used on the X-rays of younger adult subjects.

It is possible to quantify the total compression between quadriceps tendon and femoral intercondylar groove (Fcq) by introducing the angle λ. The force here was found to be significant and should not be forgotten especially when the knee is flexed to more than 90 deg. This tendon–bone compression has been discussed earlier (5, 16, 18) but its more detailed quantification in a theoretical model has not earlier been performed, as far as we know. Fig. 6d shows that Fcq was around 75% of the patello-femoral compressive force at 120 deg knee angle. In reality, this force Fcq is a sum of many forces acting peripendicularly to the intercondylar groove. The area this force acts on is not known, but is probably larger than the patello-femoral contact area, so the pressure between quadriceps tendon and femoral groove may be lower. *It cannot be excluded that this force (Fcq) might compress the upper part of the suprapatellar bursa, and in some cass even create pain.*

The biomechanical model presented in this study showed a difference between quadriceps tendon force and patellar tendon force at knee angles of 60 deg and more. Consequently, tension in the quadriceps tendon (Fq) became higher than in the patellar tendon (Fp) when the knee was flexed to 60 deg or more. In the present study the minimum ratio between Fp and Fq was 0.70 (Fig. 7). From the measurements on seven cadaver limbs made by Haxton (19), we calculate that his corresponding average ratio is 0.67 at 120 deg knee angle and 0.70 at 90 deg. Bishop & Denham (6) and Ellis et al. (12) found minimum ratios of 0.50–0.60 both in theory and in experimental measurements but the pattern of ratio change for various knee angles is very similar tc ours, with the minimum at 90 deg and an increase beyond this angle.

The quadriceps and patellar tendon forces together with the patello-femoral joint compressive force (Fcp) intersect at one point (X), (Fig. 3*a*) and at the same time the Fcp must be perpendicular to

Table II. *Anthropometrical and anatomical data of X-ray subjects*

Distances in mm. SD in parentheses

Variable	Women, $n=10$	Men, $n=10$
Age (years)	23.1 (3.1)	27.3 (5.2)
Height (m)	1.67 (0.06)	1.82 (0.04)
Weight (kg)	58.7 (8.2)	75.0 (4.9)
Femur-epicondyle breadth estimated with callipers	88.3 (5.6)	96.8 (2.5)
Femur-epicondyle breadth measured from X-ray films	72.9 (3.6)	86.3 (2.5)
Patellar height	41.2 (2.5)	47.5 (2.4)
Patellar breadth	41.9 (3.2)	48.0 (3.5)

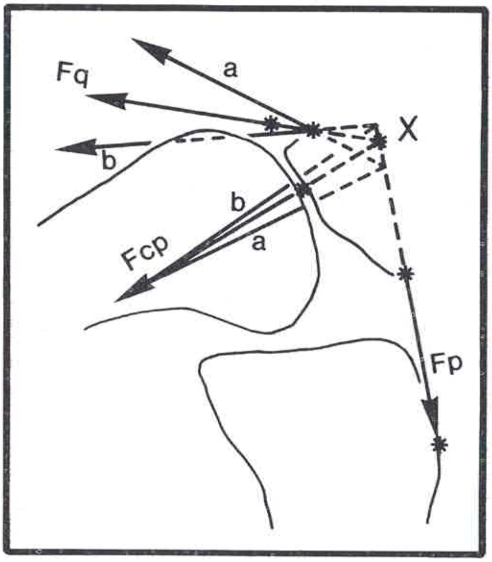

Fig. 8. Direction of patello-femoral joint compressive force (Fcp) for three theoretical directions of quadriceps tendon force (Fq). If Fq is directed more upwards (*a*), Fcp will be found to act through the joint contact area distinctly below the centre of contact, as Fcp should act perpendicularly to the joint surface. Correspondingly, if Fq is directed more downwards (*b*), Fcp will rise above the centre of patello-femoral contact. This indicates that the direction of Fq is accurately estimated if Fcp acts through the centre of the patello-femoral contact.

the patello-femoral joint cartilage if static equilibrium is to prevail. If the quadriceps tendon were bent more than what has been suggested in the present model, the force intersection point (X) would have been moved upwards. Fcp would then no longer act in the middle of the patello-femoral contact area, which would be in disagreement with basic mechanics (Fig. 8). The morphological dimensions of the patellar and quadriceps tendons are another most interesting finding (Table I). The patellar tendon was both thinner and narrower than the quadriceps tendon. These morphological ratios were 0.76 (thickness) and 0.72 (breadth) for the men, and 0.70 (thickness) and 0.71 (breadth) for the women. These arguments support the hypothesis that the minimum ratio between patellar and quadriceps tendon forces should be around 0.70.

Matthews et al. (24) suggested a special linear relationship (Fig. 9) at various knee angles for estimating the patello-femoral compressive force (Fcp). Ahmed et al. (2) showed that at knee angles of 60–120 deg, the experimentally measured Fcp is lower than what could be expected from existing theoretical biomechanical patello-femoral models. The results found in the present study may explain this incompatibility. Studying how angle ψ changes with knee angle (Fig. 4), it is seen that this relation was non-linear, particularly at knee angles of 60 deg or more. The maximum ψ angle was found at 90 deg and not at 120 deg knee angle, indicating that the patellar and quadriceps tendon forces give rise to the maximum patello-femoral joint compressive force at 90 deg knee angle. This anatomical–biomechanical fact is the main reason why Fcp reached its maximum at 90 deg and decreased beyond this angle. The magnitudes of the patello-femoral compressive forces (Fcp) found from the biomechanical model in this study may be compared with the Fcp values other theoretical models give (Fig. 9). The earlier theoretical models suggest the same force magnitudes in patellar and quadriceps tendons (24, 29, 31) but their Fcp values for knees flexed more than 60 deg are higher than those calculated from the biomechanical model presented in this study. The experimental measurements of Ahmed et al. (2) show consistently lower values than found from the present model, especially at small (or negative) knee angles but these two curves have a similar shape throughout the knee range of motion (Fig. 9).

Here may lie the reason why there is a difference in the straight knee position between the experimentally measured force (75 N, Ahmed et al. (2), Fig. 9) and the calculated compression (300 N from our model). At the straight knee the quadriceps tendon force (Fq) does not run parallel to the long axis of femur. The Fq deviation angle in relation to femur long axis is illustrated in Fig. 2 (angle φ). In this position it is easy to determine the contact point between patella and femur from the X-rays, and as the patello-femoral compressive force (Fcp) is perpendicular to the cartilage we get point X if the direction of the patellar tendon force is known. Thus, the direction of Fq is given, as this force falls through points X and Q. The difference in results at the straight knee between our model and the experimental measurement of Ahmed et al. (2) is probably due to our suggestion that the quadriceps muscle pulls the patella not only upwards but also to some degree (φ, Fig. 2) posteriorly, thus pressing the patella more against the femur. However, this force acts not only through the patello-femoral joint but also proximally to it, and consequently presses the suprapatellar fat pad against the femur (27).

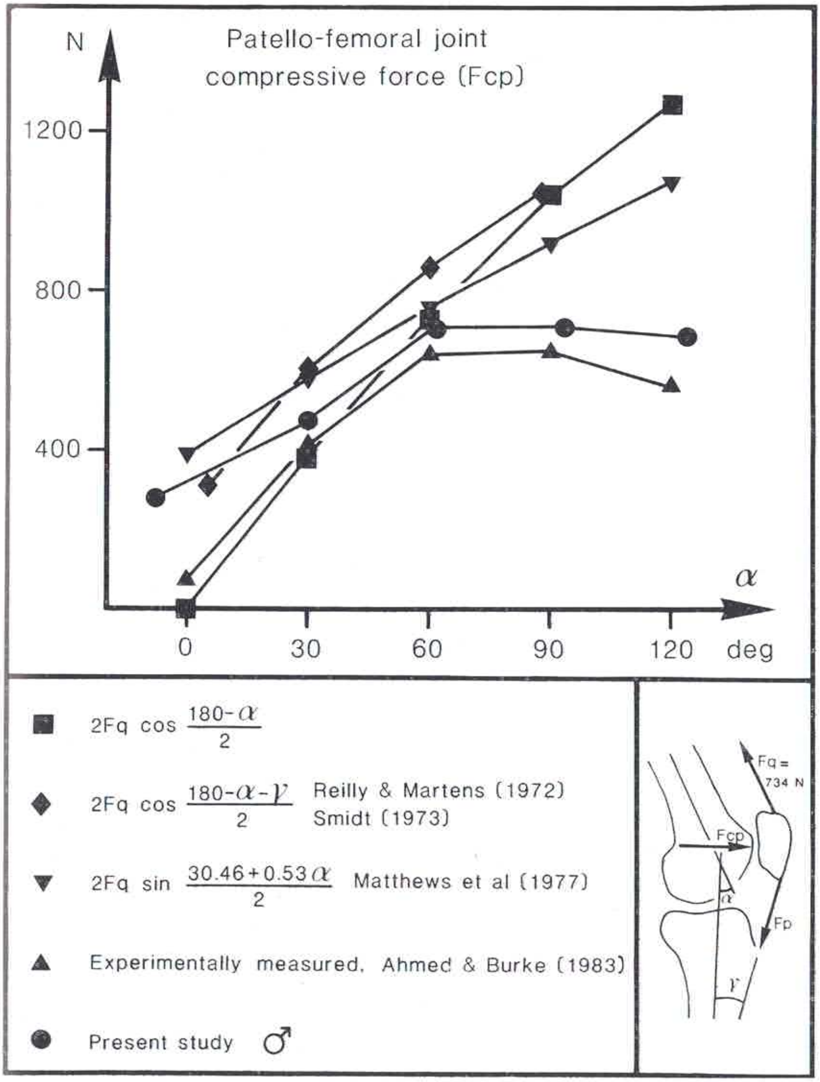

Fig. 9. Patello-femoral joint compressive force (*y*-axis) calculated by means of different patello-femoral biomechanical models at various knee angles (*x*-axis). The force in the quadriceps tendon (Fq) is 734 N. Note that the pattern of change in the present model (●) is similar to that experimentally measured by Ahmed and Burke (▲).

It should be noted that the force data diagrams shown in Fig. 6 are calculated for knee extending moment 1.0 Nm, but they can be used for other magnitudes of extending moments. If the extending knee muscular moment were 100 Nm the forces found on the *y*-axes should be multiplied by 100. A woman extending her knee corresponding to 50 Nm at a knee angle of 90 deg generates a compressive force in the patello-femoral joint, Fcp (Fig. 6*c*), of 50×39.6 N = almost 2.0 kN, or 3.4 times body weight for a 60-kg woman. A man with the knee at the same angle and exerting the same knee extending moment generates a lower compression, around 1.6 kN (or 2.2 times body weight for a 75-kg man). Consequently, if knee angle and extending moment have been determined, the diagrams in Fig. 6*a–d* may be used, also by others, in order to quantify the forces in and around the patello-femoral joint.

If the knee angle and extending muscular moment (or flexing knee load moment) about the knee have been determined, it will be possible using the model presented to quantify the magnitude of the forces in the patellar tendon (Fp), the quadriceps tendon (Fq) and the patello-femoral joint (Fcp); and the force between quadriceps tendon and femoral intercondylar groove (Fcq). Table III shows the magnitude of these forces during various activities where knee moments and angles have been taken

Table III. *Knee joint forces in men calculated for various activities*

Knee moments and angles are taken from the literature. Regarding abbreviation of forces, see Figs. 1–3 and nomenclature

Author	Activity	Knee moment (Nm)	Knee angle (deg)	Calculated forces (kN) with present model			
				Fp	Fq	Fcp	Fcq
Bresler & Frankel (7)	Level walking	61	20	1.4	1.5	0.9	0
Kelley et al. (21)	Rising	110	90	2.5	3.6	3.5	1.1
Andriacchi et al. (3)	Ascending stairs	54	65	1.2	1.6	1.5	0
	Descending stairs	147	60	3.2	4.3	4.0	0
Ekholm et al. (9)	Lifting	50	90	1.2	1.7	1.6	0.5
Lindahl et al. (22)	Isometric max	225	60	4.8	6.3	6.1	0
Smidt (31)	Isometric max	120	60	2.6	3.5	3.4	0
Ekholm et al. (10)	Isometric max	198	90	4.6	6.5	6.3	2.0

from the literature. The forces are calculated for men. Women, for the same knee angle and moment, would have about 20% higher values due to shorter patellar tendon moment arms (26). Andriacchi et al. (3) determined among men the flexing knee load moment and knee angle during stair walking. When ascending stairs, there is a knee moment of 54 Nm and a knee angle of about 65 deg giving (from Fig. 6*a–c*, males) $\mathrm{Fp} = 54\ \mathrm{Nm} \times 22\ \mathrm{N}/1.0\ \mathrm{Nm} = 1.2\ \mathrm{kN}$, $\mathrm{Fcp} = 1.6\ \mathrm{kN}$, $\mathrm{Fq} = 1.6\ \mathrm{kN}$. Considering ordinary walking (7), it is seen that the maximum knee flexing moment is about 60 Nm, but the knee angle is not more than 20 deg when this flexing load occurs. This is the reason why Fcp is not so high. When lifting a 12.8 kg box (9) the knee angle and knee flexing load moment are highest in the beginning of the lifts with bent knees (about 90 deg and 50 Nm) giving an Fcp of 1.6 kN (men). Fcp will reach values as high as 6 kN during a knee extending isometric maximum contraction.

The forces arising in the female patello-femoral joints will be higher than for men if the knee moment is the same (Fig. 6*a–d*). During walking and stair-climbing the knee load moment is generally proportional to body weight. Usually, women weigh less than men and their knee load moment will therefore be lower. At the same time the contact area of the joint compressive force is probably lower among women in general due to smaller knees and patellae (Table I). If a woman weighs the same as a man she exposes her joints to about the same load moments but the joint forces will be higher than for a man's as will the pressure on the cartilage due to higher compressive forces and smaller contact areas. Consequently, *overweight women are exposed to higher patello-femoral joint stresses than men of corresponding weight. This might explain why patello-femoral joint osteoarthrosis is more frequent among women than men and why overweight women are especially vulnerable. The same considerations may be applied to the tibiofemoral and hip joints as the sex anatomical differences are significant here too (25, 26).*

Earlier theoretical models of patello-femoral joint biomechanics (24, 29, 31) show that the patello-femoral joint compressive force (Fcp) increases with increased knee flexion angle (Fig. 9). The results from our model shows that Fcp was lowest at straight knee angles; but it was of the same magnitude at knee angles of between 60 deg and 120 deg (Fig. 6*c*). Thus, significantly higher Fcp is not caused by flexing the knee to 120 deg compared with 60 deg if the knee moment is constant. *A painful patello-femoral joint sensitive to high stresses (e.g. osteoarthrosis) is better exercised at straighter knee angles so that high compressive forces are avoided.* Note that the patello-femoral joint receives about the same level of load between 60 deg and 120 deg, so for patients with pain elicited from this joint there is no reason to avoid 120 deg more than 60 deg. Exercises aiming at an optimal range of motion is of course also necessary, but should be undertaken, for knee angles of 30 deg and more, mainly passively, i.e. with no or only very little load.

Patients with load-elicited pain from the patello-femoral joint might be advised to avoid knee angles above 30 deg under loaded conditions such as;

deep squatting, lifting objects from the floor with flexed knees, ascending or descending stairs. The reason for this is that the knee extensor apparatus is less activated at these low knee angles and the patello-femoral compression is low. A patello-femoral arthrosis patient might even be advised to lift with straight knees and flexed trunk (if this does not cause low back pain) or to use technical aids.

Quantification of physiological forces in and around the patello-femoral joint is valuable when patients with various kinds of knee disorders have physical therapy. Increased knowledge of the magnitude of the forces in the patello-femoral joint makes it possible to develop exercise programmes that are less harmful to injured, diseased or weak tissues. Each patient, with his specific diagnosis, may in this way be given a more individualized exercise programme. The biomechanical model presented contributes to the development of such programmes, and can also be applied to quantifying patello-femoral forces during other knee extending activities.

CONCLUSIONS

1. The patellar tendon was found to be 25–30% thinner and narrower than the quadriceps tendon, and the forces in these tendons (Fp and Fq) at knee angles of 60–120 deg were found to have a relation of about 0.70–0.80. At straighter knee angles, the two forces were of the same magnitude.

2. For a constant knee extending moment, the patello-femoral joint compressive force (Fcp) was found to reach a maximum at 90 deg knee angle and to decrease in magnitude beyond this knee angle. Fcp and Fq were about the same from 60 deg to 120 deg knee angle.

3. Above knee angles of 60 deg a compressive force (Fcq) was found between femoral intercondylar groove and quadriceps tendon. This force increased linearly with knee angle and its magnitude was estimated.

4. Women were found to develop generally higher patello-femoral forces than men for the same knee extending muscular moments.

5. If the knee extending muscular moment and knee angle have been determined for a specific knee extending activity or exercise, the biomechanical model presented may be used generally in order to quantify and predict the forces in and around the patello-femoral joint for that specific activity.

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