

Mechanics of the patellar articulation

Effects of patellar ligament length studied with a mathematical model

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We investigated the influence of the length of the patellar ligament on (1) the relative positions of the ligament, patella, and quadriceps tendon, (2) the location of the patellofemoral contact point, (3) the force of the quadriceps femoris muscle, and (4) the patellofemoral compression force for 0-120° flexion-extension angles of the knee. For this purpose, we used a mathematical model, describing movements and forces in the sagittal plane. The anatomic parameters for the model were obtained from five autopsy knees. The patellar ligament length appeared to influence the mechanical behavior of the patellar articulation considerably. The magnitude of the induced changes was determined by the length of the ligament and by the flexion-extension angle of the knee.

There exists a complex mutual relationship between the mechanism of the patellar articulation and the wrapping movement of the distal part of the quadriceps muscle around the femur. Various anatomic parameters, notably the length of the patellar ligament and the dimensions of the patella, determine the mechanics of the patellar articulation (Van Eijden et al. 1985, 1986). There is a lack of analytical models that incorporate both the morphology and movements and forces at different flexion-extension angles of the knee. More restricted models (Reilly & Martens 1972, Smidt 1973, Perry et al. 1975, Matthews et al. 1977) have assumed an equal force in the patellar ligament and quadriceps muscle. However, it has been shown both experimentally (Ellis et al. 1980, Huberti et al. 1984) and mathematically (Van Eijden et al. 1986) that the ratio between patellar ligament force and quadriceps muscle force changes with the flexion-extension angle, influencing the muscle force required to exert a certain extension torque and thus affecting the compression force of the patella.

Variations in the geometric configuration of the patellar articulation have been considered major etiologic factors in the degeneration of the patellar articular cartilage (Wiberg 1941, Ficat & Hungerford 1977, Bentley & Dowd 1984); both abnormal gliding paths and high contact pressure have generally been held responsible for damage of this cartilage.

We applied a mathematical model to analyze the influence of patellar ligament length on (1) the relative position of the ligament, patella, and quadriceps tendon, (2) the location of the assumed patellofemoral contact point, (3) the ratio between patellar ligament force and quadriceps muscle force, and (4) the ratio between patellar compression and quadriceps muscle forces.

Materials and methods

Patellofemoral mechanics. The patellar articulation (Figure 1) was treated as a two-dimensional chain describing movement and force components in the sagittal plane (Van Eijden et al. 1985); it consisted of patellar ligament, patella, quadriceps muscle and the patellofemoral articulating surfaces. Between these elements, forces were exerted. Static situations in which the quadriceps

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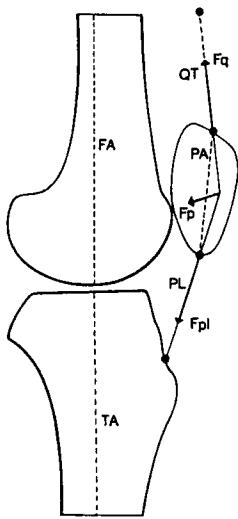


Figure 1. Lateral diagram of the knee.

FA femoral axis
TA tibial axis
PA patellar axis
PL patellar ligament
QT quadriceps tendon
 F_q quadriceps muscle force
 F_{pl} patellar ligament force
 F_p patellofemoral compression force.

muscle exerts a force F_q , counteracted by a reaction force F_{pl} in the patellar ligament were considered. Neglecting friction, the resultant force of F_q and F_{pl} , i.e., the patellar compression force F_p , should be applied perpendicular to the articulating profiles at the presumed point of contact between the patella and femur. For each flexion angle of the knee, the conditions of static equilibrium demand that the position of the patella should be such that the sum of forces and the sum of moments acting on it are zero. While the geometry of the articulation remains unaltered during flexion, the patella is maintaining its contact with the femoral groove, and its apex remains at a constant distance (equal in length to the patellar ligament) to the tibial tuberosity. At large flexion angles, the quadriceps tendon will also contact the femoral groove, and will start to bend over it.

The mechanics and geometry of the patellar articulation can be described by a mathematical model with nine nonlinear equations (Van Eijden et al. 1986). In our model, values of the morphological parameters were obtained from lateral view radiographs of autopsy knees. Each flexion angle of the knee was characterized by a specific position of the tibial tuberosity. This position was measured between 0° and 120° of flexion at 10° increments.

Solution of the set equations was achieved by a numerical procedure. The following was calcu-

lated as a function of the flexion-extension angle: the relative position of the patellar ligament, patella, and quadriceps tendon, the location of the patellofemoral contact point, the value of the patellar compression force, and the force in the patellar ligament.

Measurements. Five legs (two right and three left) obtained from 5 male embalmed cadavers (64–74 years) were used. Radiographs and macroscopic examination of the specimens were normal. The femoral condylar width was measured (Mensch & Amstutz 1975); the mean width was 84 (75–92) mm. Patellar ligament length, patellar length, and ratio patellar ligament length to patellar length were determined according to Insall & Salvati (1971); mean values were 48 (45–52) mm and 1.0 (0.9–1.1), respectively, which is normal.

Calculations were performed for normal and simulated values of the anatomic parameters; i.e., the length of the patellar ligament was given simulated values of 75, 85, 95, 105, 115, and 125 per cent of the normal length. The mean ratios between patellar ligament length and patellar length in case of the simulated ligament lengths were, respectively, 0.7 (range for the five knees 0.6–0.8), 0.8 (0.7–1.0), 0.9 (0.8–1.1), 1.0 (0.9–1.2), 1.1 (1.0–1.3), and 1.2 (1.1–1.4). Insall & Salvati (1971) considered patellar position in relation to the femur as abnormal if the ratio was more than 1.2 (high position) or smaller than 0.8 (low position).

For all the knees and flexion angles, mean angles were calculated between patellar ligament (PL) and tibial axis (TA), quadriceps tendon (QT) and femoral axis (FA), and QT and PL. To obtain a precise insight in the variation of data, one would require a number of 91 (13 angles, 7 ligament lengths) standard deviation values (SD). We reduced this large number of data by giving mean values and ranges of the SD calculated for the 75 and 125 per cent ligament lengths (see legend to the figures).

An estimation of the influence of patellar ligament length on the moment arm length of the patellar ligament force was obtained by taking the perpendicular distance between tibiofemoral contact point of the lateral condyles, identified in the radiographs, and the patellar ligament, calculated by the model.

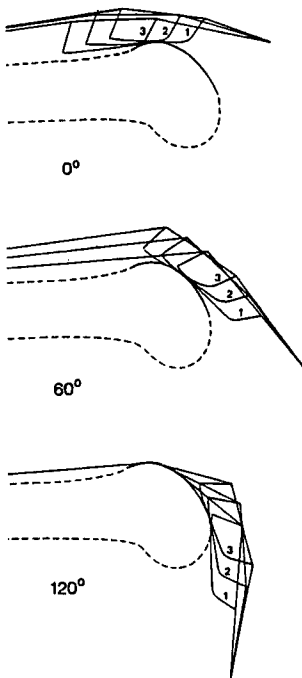


Figure 2. Relative positions of patellar ligament, patella, and quadriceps tendon at 0°, 60°, and 120° of flexion.
1: PL = 75 per cent, 2: PL = 100 per cent, 3: PL = 125 per cent.

Results

Position of patellar ligament, patella, and quadriceps tendon. For all flexion angles the contact point is located more proximally on the femoral profile with a long ligament and more distally with a short ligament (Figure 2); for all knees and all flexion angles, the mean amount of contact-point displacement was maximal (10 per cent of the profile length) for both the longest and shortest ligament. The contact point on the patellar profile was displaced more distally by a long ligament and more proximally by a short ligament (mean maximal displacement 10 per cent). The total amount of contact-point displacement on the profiles throughout the entire flexion range was not influenced by patellar ligament length variations.

In a normal knee, the patellar ligament undergoes a backwards rotation of approximately 35° relative to the tibia. From the tibial tuberosity, the patellar ligament points anteriorly (away from the tibial axis) between 0° and 80° of flexion, runs parallel to the tibial axis at 80°, and points posteriorly between 80° and 120° (Figure 3). Ligament length had a negligible effect on this angle at flexion angles between 50° and 60°.

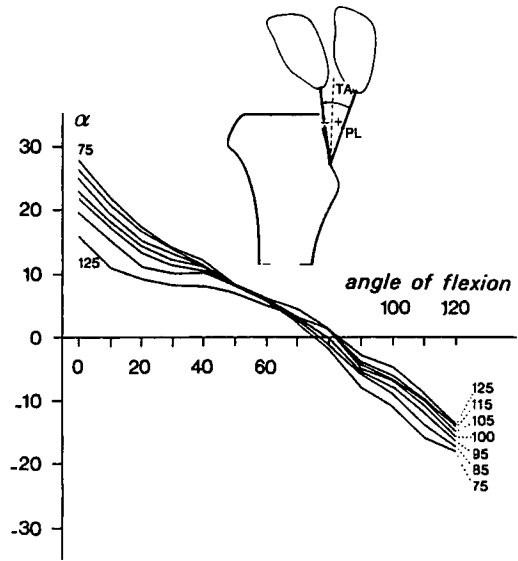


Figure 3. Angle (α) between patellar ligament and tibial axis vs flexion angle for different ligament lengths (75–125 per cent). SD 75 per cent: 5.4° (mean), 5°–8° (range); 125 per cent: 5.1°, 3°–7°.

However, in both the first and last part of flexion the angle became smaller in case of a long ligament and larger in case of a short ligament. Thus, the total amount of angular change of the patellar ligament during flexion was reduced by a long ligament and increased by a short ligament.

As the orientation of the patellar ligament (angle α) changes with ligament length, the moment arm length of the patellar ligament force is also affected, particularly at the extremes of the flexion-extension range. The effect of ligament length seemed to be rather small and reached its maximum (8 per cent) at 0° for a long, and at 120° for a short ligament (Figure 4).

In case of a normal ligament length, a slight change of the angle between QT and FA occurs in the first 70° of flexion and a rapid change in the last 50° (Figure 5). From 70–120° of flexion, the quadriceps tendon bends over the femoral intercondylar groove. In a knee with a long ligament, the tendon contacted the groove at a larger flexion angle than in a knee with a short ligament. The change of the angle between the tendon and the femur was therefore smaller in knees with a long ligament.

The angle between QT and PL (Figure 6) is

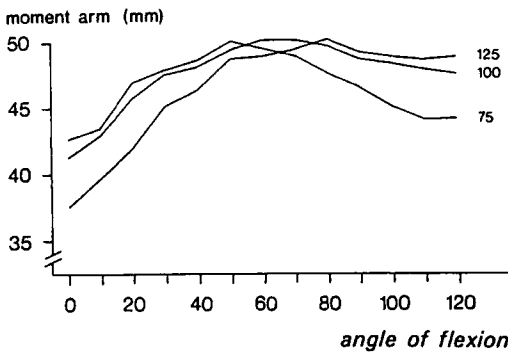


Figure 4. Moment arm length of F_{pl} vs flexion angle. SD 100 per cent: 2.1 mm (mean), 1.7–3.7 mm (range).

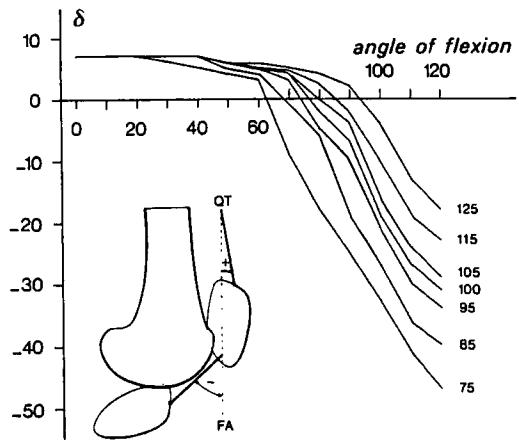


Figure 5. Angle (δ) between quadriceps tendon and femoral axis vs flexion angle. SD 75 per cent: 4.7° (mean), 2°–8° (range); 125 per cent: 3.2°, 3°–5°.

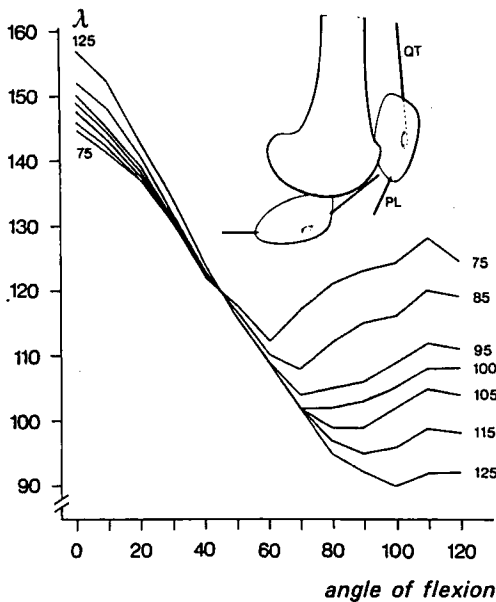


Figure 6. Angle (λ) between quadriceps tendon and patellar ligament vs flexion angle. SD 75 per cent: 5° (mean), 1°–7° (range); 125 per cent: 5°, 3°–6°.

determined by the orientation of both the patellar ligament and quadriceps tendon in relation to the patella. A long ligament resulted in a slight increase in the QT-PL angle between 0° and 40° of flexion and in a relatively large decrease between 40° and 120°. A short ligament decreased the angle between 0° and 40° and increased it between 40° and 120°.

Ratio between patellar ligament and quadriceps muscle forces. Because no absolute forces were determined with the model, patellar ligament

force was expressed as the ratio F_{pl}/F_q . In the normal knees, this ratio (Figure 7) decreased from 1.1 at maximal extension to 0.55 at 80°, and then changed slightly at larger flexion angles. Thus, patellar ligament force was somewhat larger than the muscle force between 0° and 30° and became considerably smaller between 30° and 120°. Ligament length had the largest effect in the first 60–80° of flexion. In this flexion range, long ligaments increased the ratio, whereas short ligaments decreased it. At larger flexion angles a small reverse effect occurred.

Ratio between patellar compression and quadriceps muscle forces. The patellofemoral compression force to muscle force ratio (F_p/F_q) was lowest at maximal extension, increased between 0° and 80° of flexion and then showed slight variations at larger flexion angles (Figure 8). Ligament length variations had a negligible effect on the ratio at 20° of flexion. Between 0° and 20°, long ligaments decreased it slightly, whereas short ligaments gave a small increase. A relatively large opposite effect occurred at angles between 20° and 120°.

Discussion

In contrast to previous models of the patellar articulation (Reilly & Martens 1972, Smidt 1973,

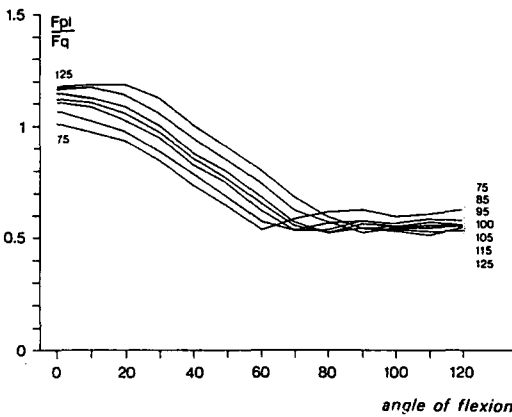


Figure 7. Ratio F_{pl}/F_q between patellar ligament force and quadriceps force vs flexion angle. SD 75 per cent: 0.09 (mean), 0.07–0.01 (range); 125 per cent: 0.06, 0.02–0.08.

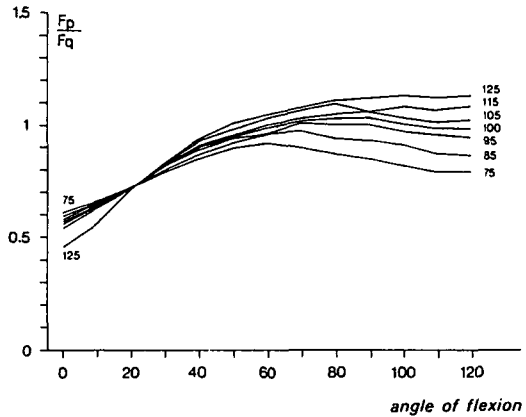


Figure 8. Ratio F_p/F_q between patellofemoral compression force and quadriceps force vs flexion angle. SD 75 per cent: 0.06 (mean), 0.02–0.09 (range); 125 per cent: 0.07, 0.03–0.1.

Perry et al. 1975, Bandi 1978), ours predicts relative displacements between quadriceps tendon, femur, patella, patellar ligament, and tibia, as well as the force in the patellar ligament and the patellar compression force. It takes into account the wrapping of the muscle tendon around the femur. Recently, Nisell (1985) calculated knee forces, also taking into account relative displacements in the distal part of the quadriceps muscle.

Two aspects have so far not been considered: viz., ligament and articular cartilage deformation. Furthermore, the contact point used is a simplification of the really existing contact area. Also, contacts at the medial and lateral articular facets are ignored, and therefore joint pressures and their distributions cannot be calculated. Several experiments indicate that total contact area increases during flexion (Henche et al. 1981, Huberti & Hayes 1984). Hence, articular pressures cannot be assumed to be proportional to the compression force, generated by our model.

It appears from our results that the length of the patellar ligament has a profound effect on the movements of the patellar ligament, patella, and quadriceps tendon relative to the femur and tibia during knee flexion. Because the influence of the length of the patellar ligament is so marked, the mechanical demands imposed on the structures of the joint may also be different for different ligament lengths.

The patellar compression force depends on the angle between quadriceps tendon and patellar

ligament (Figure 6). This angle closed in the first part of the flexion and consequently the compression force ratio increased. However, at larger flexion angles the angle remained approximately constant. This is due to the bending movement of the quadriceps tendon over the intercondylar groove. Hence, a further increase of the patellofemoral compression force ratio is prevented.

In a knee with a short ligament the tendon contacts the femur at a smaller flexion angle than in one with a normal ligament; with a long ligament the contact starts to occur at a larger flexion angle. Therefore, the patellar compression force ratio reaches smaller values in a knee with a short ligament and larger values in one with a long ligament.

The tendofemoral compression force is proportional to the angle between the lines of pull of the proximal and distal part of the quadriceps tendon (Van Eijden et al. 1986). For a given flexion angle, this angle becomes larger in a knee with a short ligament and smaller in a knee with a long ligament. The tendofemoral contact force differs accordingly. For example, at 120° of flexion the magnitude of the force is 0.8 F_q , 0.5 F_q and 0.3 F_q in cases of, respectively, a short (75 per cent), normal and long (125 per cent) ligament. Note, that in cases of a short ligament, the tendofemoral compression force ratio is relatively high and the patellar compression force ratio relatively low. In case of a long ligament the reverse is true.

The anteroposterior force applied to the tibia (F_{pls}) depends on the angle between patellar

ligament and tibial axis ($F_{pl_s} = F_{pl} \sin \alpha$). Shortening of the patellar ligament leads to an increase of α , particularly at the extremes of the flexion-extension range. As a consequence, at 0° of flexion, for example, a short ligament increased the anteroposterior force by 17 per cent relative to a normal ligament; in a long ligament the force decreased by 30 per cent. Because the anterior-posterior force is resisted by the cruciate ligaments, patellar ligament length may influence the tension developed in these ligaments.

The quadriceps muscle force required to produce a certain extension moment depends on the ratio between patellar ligament force and quadriceps force. The patellar articulation cannot be considered as a simple pulley, ensuring equal tensile forces in the patellar ligament and quadriceps tendon. The changing F_{pl}/F_q ratio is influenced by patellar ligament length. A long ligament increased the ratio in the first part of flexion (maximal 23 per cent at 70° with a 125 per cent ligament), and decreased it about 10 per cent at larger flexion angles. This results in a respective decrease and increase of the muscle force necessary to generate a certain extension moment. The reverse effect is seen in case of a short ligament: the decrease of the F_{pl}/F_q ratio in the first part of flexion (maximal 18 per cent at 60° with a 75 per cent ligament) requires a larger muscle force, and the increase of the ratio (about 15 per cent) in the second part of flexion a smaller force.

The mechanical advantage of the quadriceps muscle force depends not only on the F_{pl}/F_q ratio, but also on the length of the moment arm of the patellar ligament force. The results show that the influence of patellar ligament length on the mechanical advantage of the quadriceps muscle is

primarily caused by F_{pl}/F_q ratio changes and not by variations in moment arm length of F_{pl} .

It can be concluded that the patellar articulation does not act as a simple hinge and that the quadriceps muscle has an important motion guiding role. Reversely, the behavior of the joint influences the transmission of force from the muscle belly to the tibia. It should be emphasized that the force applied to the tibia is smaller than the force exerted by the quadriceps muscle belly, especially at large flexion angles.

With respect to the influence of patellar ligament length on the mechanics of the patellar articulation, no data are available that allow a comparison with our results. Our study does not answer the question at which ligament length the mechanical demands imposed on the joint can be considered as unphysiological. Insall et al. (1975) and Bandi (1978) suggested a relationship between patella alta, chondromalacia, and arthrosis. Our results show an increase of the relative patellar compression force at flexion angles larger than 20° ; this may be a causative factor. Also, the decrease of the angle between patellar ligament and quadriceps tendon may possibly influence the amount of, for example, the tensile and compressive stresses subjected to the patella. An increase of these stresses has been related to patellar articular cartilage lesions (Townsend et al. 1977, Minns et al. 1979).

Patella baja has been associated with Osgood-Schlatter's disease (Lancourt et al. 1975). Our results indicate that in patella baja the tibial tuberosity may be subjected to relatively large anteroposterior forces. These larger forces may play a role in the etiology of the avulsion of the tibial tuberosity.

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