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In vitro patellofemoral joint force determined by a non-invasive technique

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Abstract

Objective. To develop a method of measuring the magnitude, direction and point of application of the patellofemoral force (PFF), directly and non-invasively in three dimensions.

Design and methods. The compressive PFF is replaced exactly with a tensile force applied to the front of the patella. The magnitude, direction and point of application of the tensile force are then measured. The technique was applied to six normal knees mounted in a 6 degree of freedom rig with quadriceps tendon tension force (QTF) applied to balance a flexing load and to simulate weight bearing.

Results. The PFF was greater than in previous more invasive *in vitro* studies but the results correlated well with recent theoretical analyses. At 20° knee flexion the force was 75% of QTF. It increased to 100% of QTF at 60° knee flexion and remained at this level at higher angles of flexion. The lateral vector of the PFF was small compared to the sagittal plane vector and became negligible beyond 60° of knee flexion. The point of application of the PFF to the patella moved proximally and medially with knee flexion.

Conclusions. A new and reliable method of measuring PFF non-invasively and in three dimensions has been developed.

Relevance

A new technique is described for measuring the PFF *in vitro*. The non-invasive nature of the technique makes it useful for studying the effect on the PFF of simulated pathological conditions, surgical procedures and different types of knee replacement. © 1997 Elsevier Science Ltd. All rights reserved.

Key words: Patellofemoral force, *in vitro* measurement technique, knee replacements

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Introduction

The patellofemoral force (PFF) has proved difficult to quantify because of the inherent problems in measuring compressive forces between joint surfaces while maintaining their normal relationship and mechanics[1]. Various invasive techniques have been used. Thin pressure-sensitive films have been used to record the contact stress and the area over which the force is applied[2,3], from which the total force can be estimated. Single or multiple electrical transducers have been inserted beneath or within the articular cartilage[4,5], or between the two halves of the divided patella[6,7]. The patellofemoral force has also been deduced from measurements of the patellar tendon force (PTF), quadriceps tendon force (QTF), and the angle between them[8–10]. These techniques have produced different estimates of the PFF, most of which have been substantially lower than those predicted by theoretical analysis of the extensor mechanism[2,11–13].

We describe a new technique for measuring the PFF which, unlike other techniques, does not involve opening the joint or disturbing its anatomical relation-

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ship. The compressive PFF is replaced by a tensile force applied to the front of the patella. The magnitude, direction and point of application of this tensile force is then measured.

Methods

Theoretical basis

A free-body diagram of the patella includes three main forces acting on it. For equilibrium these three forces must be coplanar and their lines of action must intersect at a point, the centre of force of the patella (Figure 1a). Our technique consists of replacing the compressive PFF with a tensile force (TF) which can more easily be measured (Figure 1b,c). For equilibrium to be maintained, the applied TF force should have exactly the same magnitude, line of action, and point of application as the PFF it replaces. The TF is considered to have replaced the PFF exactly when the patella just lifts off the femur (incipient lift-off) without the patella rotating or translating.

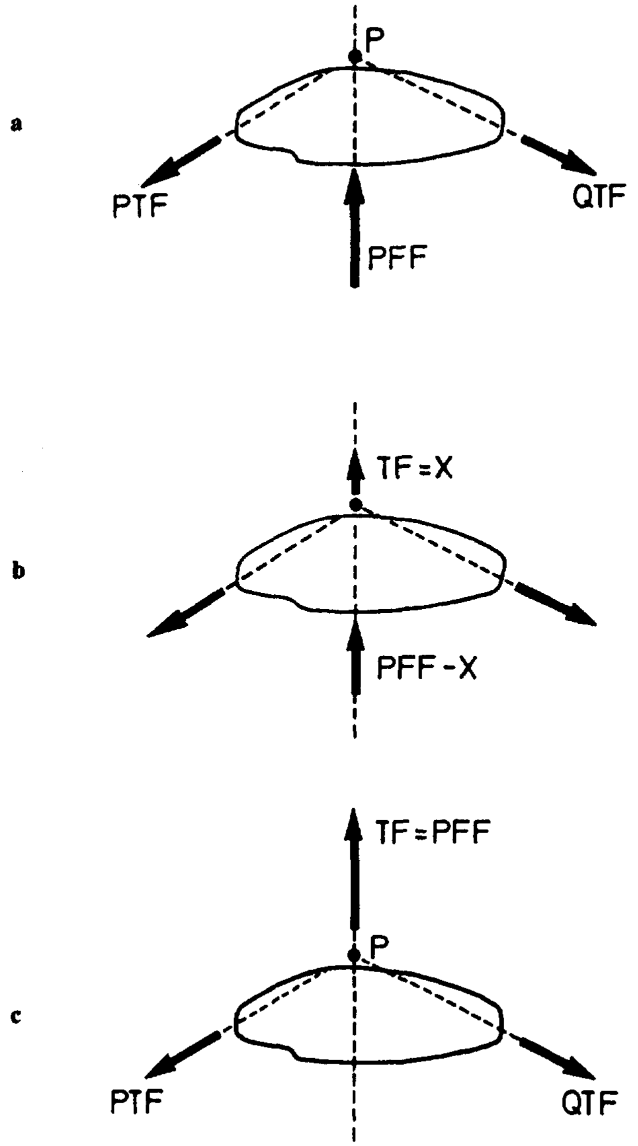

Figure 1. Principles of the experiment. (a) The three forces acting on the patella: the patellar tendon force (PTF), quadriceps tendon force (QTF), and patellofemoral force (PFF), intersect at a point (P), the centre of force. (b) The PFF is measured by applying a tensile force (TF) to the anterior aspect of the patella, through P. The TF is gradually increased until it replaces the PFF (c), provided that both forces have the same line of action.

Specimens

Six fresh human cadaver knees were taken at autopsy and quick frozen to −20°C. Immediately prior to testing, the knee was thawed to room temperature and prepared by resecting the skin, subcutaneous fat and muscle bellies. The tendons and ligaments were retained and the joint capsule, including the retinaculae, was left intact. The tibia and femur were sectioned approximately 20 cm from the joint line. Intermedullary rods were inserted into the bones and fixed with cement. The femoral rod was used to secure the specimen to the rig.

Testing rig

The specimen was held with the femur fixed and the tibia unconstrained (Figure 2a). To test the knee at flexion angles between 20 and 80° the femur was fixed at 45° to the horizontal; for flexion angles between 100 and 120° the femur was fixed vertically. These positions facilitated application of the TF to the patella over the required range of angles.

A 0.5-kg weight was hung from the tibial rod at a distance of approximately 45 cm from the joint line, apply a flexing moment of about 2.2 Nm at the knee. The flexing moment was balanced by tension in the quadriceps cable (Figure 2a) attached at one end to the quadriceps tendon and at the other end to a turnbuckle. The angle of knee flexion was controlled by adjusting the length of the cable. Tension in the cable was monitored with a strain-gauged proving ring.

An aluminium bracket (Figure 2b) was screwed to the front of the patella for the attachment of the patellar tensile cable. The bracket was designed to allow the attachment point of the cable to be adjusted in the transverse plane by a slider mechanism and in the sagittal plane by a series of holes. The direction of the cable was also infinitely adjustable and was recorded in the sagittal and transverse planes using a spirit level and protractor. The tension in this cable was also controlled by a turnbuckle and monitored with a strain gauged proving ring.

Experimental procedure

1. The specimen was mounted in the rig and the tibial load applied. The knee flexion angle was set by adjusting the length of the quadriceps cable.
2. The line of action and point of application of the patellar tensile cable were varied by trial and error

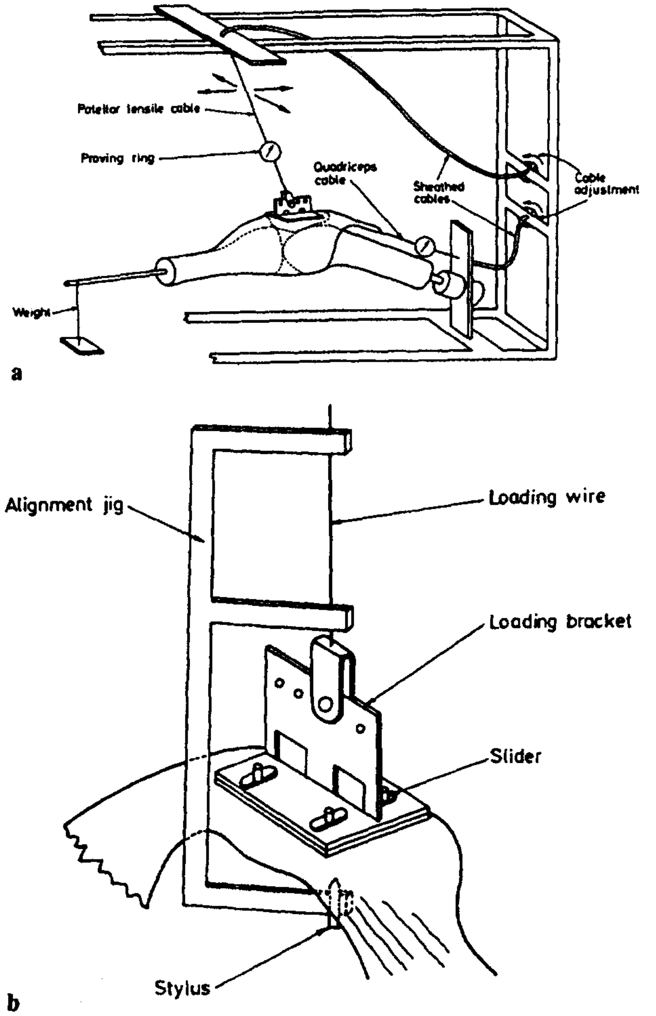

Figure 2. (a) Schematic diagram of the testing rig with the specimen mounted and the tibial load applied. The quadriceps cable was parallel to the femoral shaft. The line of action, point of application and magnitude of the patellar tensile cable were adjusted so that there was no movement of the patella during 'lift off'. (b) To determine the centre of pressure, the line of action of the patellar tensile cable was projected onto the articular surface of the patella with a jig.

until there was no rotation or translation of the patella at the point of incipient lift-off. (TF was then taken to be colinear with PFF.)

3. The magnitude of the PFF was measured by gradually increasing the tension in the cable (Figure 1b). At first no change was observed in the quadriceps force and the tibia did not move, indicating that the patellar tendon force had not changed either. Incipient lift-off was detected by observing a slight extension movement of the tibia and, simultaneously, a small increase in QTF. At this point, the PFF was deemed to have been replaced exactly by TF, the value of which was recorded (Figure 1c).
4. The direction of PFF. The orientation of the patellar cable in relation to the patella in the sagittal and transverse planes was measured using a protractor. The angle between the quadriceps cable and the patella tendon (the patellar mechanism angle) was measured with a goniometer.
5. Centre of pressure of PFF. The PFF is applied to the patella over an area but its resultant intersects the articular surface at a point, the centre of pressure of the PFF. The points of intersection of the lines of action of TF with the articular surface of the patella were identified after all the measurements on each specimen had been completed. The patella was excised with its tension-loading bracket still attached and held horizontally in a vice. The tension wire was reset in one of its various orientations relative to the bracket recorded during the test and an E-shaped jig was used to mark the corresponding centre of pressure on the articular surface of the patella (Figure 2b). The vertical distance of the marked point from the inferior limit of the articular surface and its horizontal distance from the median ridge of the patella were recorded and these distances were expressed as fractions of the height and width of the articular surface of the patella. This procedure was repeated for each angle of flexion, the series of points defining the track of the centre of pressure across the articular surface.
6. Patellar tendon force. The technique determines the directions and magnitudes of the quadriceps and patellofemoral forces. The remaining force, the patellar tendon force was calculated by vector addition of the PFF and QTF.

Results

Six specimens were studied. The results are summarized in Table 1. In this Table the forces are expressed non-dimensionally as a proportion of the QTF.

Patellofemoral force magnitude

At 20° flexion, PFF was 75% of QTF, increasing to 100% at 60°, and remaining at about 100% at higher

Table 1. Mean and standard deviation (SD) of the results from six specimens. The forces (patella femoral force (PFF) and patella tendon force (PTF)) are expressed non-dimensionally as a proportion of the quadriceps tendon force (QTF). The vertical distance of the centre of pressure from the interior limit of the articular surface and the horizontal distance from the median ridge are expressed as a percentage of the height and width of the articular surface. The direction of the PFF in the sagittal plane (Figure 4) and the direction of the PFF in the transverse plane (Figure 5) as expressed in degrees

Flexion	20°		40°		60°		80°		100°		120°	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
PFF/QTF	0.75	0.07	0.87	0.05	0.99	0.04	1.00	0.06	0.95	0.05	1.03	0.09
PTF/QTF	1.11	0.06	0.99	0.06	0.80	0.08	0.55	0.08				
Vertical distance (%)	17	6	33	10	49	10	65	13	75	14	85	11
Horizontal distance (%)	17	10	10	7	2	8	2	10	4	11	9	18
PFF sagittal angle	4.7	3.4	0.3	5.0	−3.5	5.6	−4.5	6.	−3.	3.3	−3.6	4.2
PFF transverse angle	11.7	2.6	6.3	2.1	2.7	2	0.7	1.2	−0.5	0.8	−0.5	1.6

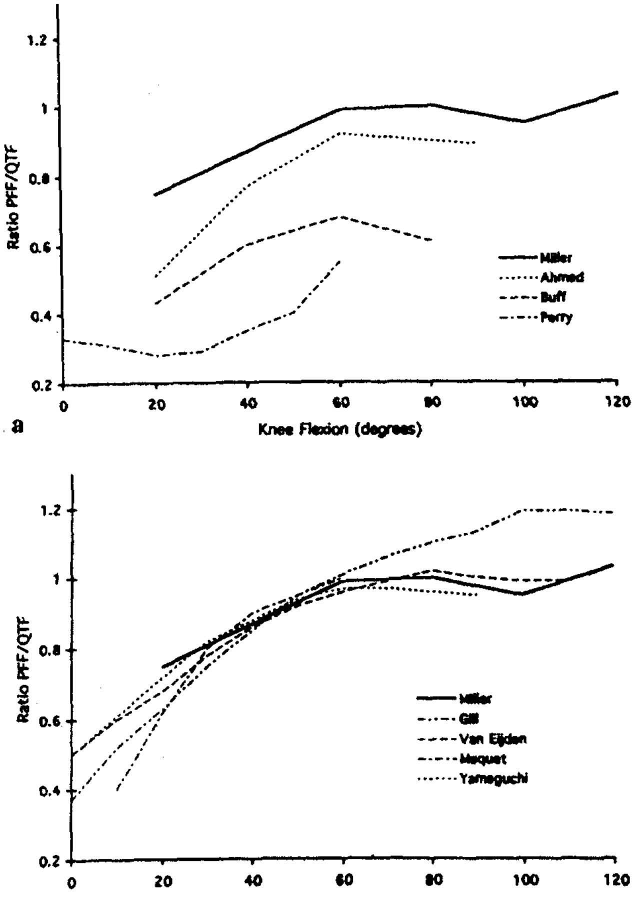

Figure 3. The patellofemoral force (PFF) expressed as a proportion of the quadriceps tendon force (QTF). The current study is compared to previous (a) *in vitro*[2,6,10] and (b) theoretical studies[11,13-15].

angles of flexion. These results are presented graphically together with the results of some previously published *in vitro*[2,6,10] (Figure 3a) and theoretical studies[11,13-15] (Figure 3b).

Patellofemoral force direction

The sagittal plane orientation of the PFF in relation to the patella is illustrated in Figure 4 and the transverse plane orientation in Figure 5. The PFF was resolved into sagittal and transverse components and the ratio of these is presented in Figure 6.

Patellofemoral force centre of pressure

The position of the centre of pressure of the PFF on the articular surface of the patella moved proximally and medially during knee flexion, as shown schematically in Figure 5. The movement of the centre of pressure matched the changing pattern of the contact areas as previously reported[16,17].

Patellar tendon/quadriceps tendon force ratio

The ratio of the measured quadriceps tendon force to the calculated patellar tendon force is presented in Figure 7 and compared with the results of other *in vitro*[3,8] and theoretical studies[13,15].

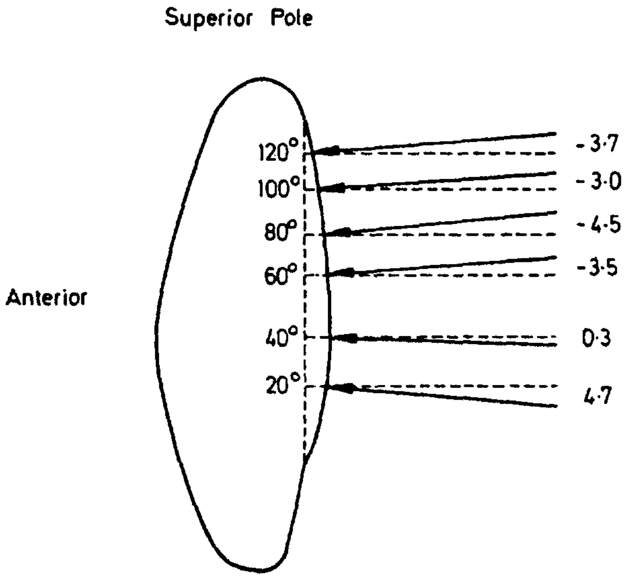

Figure 4. Schematic diagram of patella in the sagittal plane, illustrating the direction and point of application of the PFF on the articular surface for knee flexion angles 20–120°.

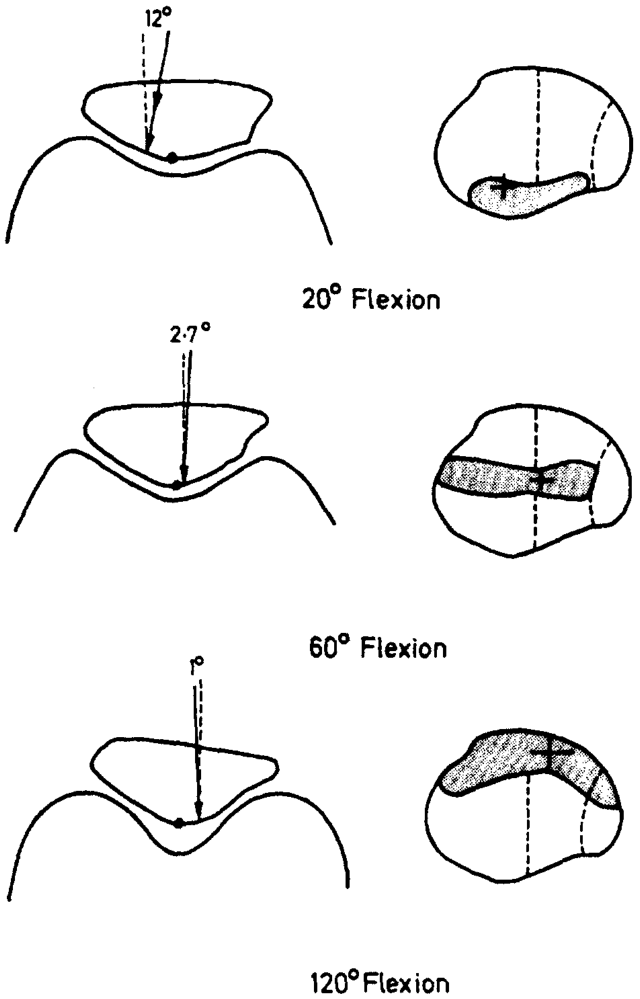

Figure 5. Transverse plane views of patella with the direction and point of application of the PFF shown. The median ridge is marked with a heavy dot and the medial sides is on the right. Articular surface of patella with the centre of pressure of the PFF for the current study (marked with a cross) compared with the contact area (shaded) observed by Goodfellow *et al.*[16]. Each arm of the cross is one standard deviation.

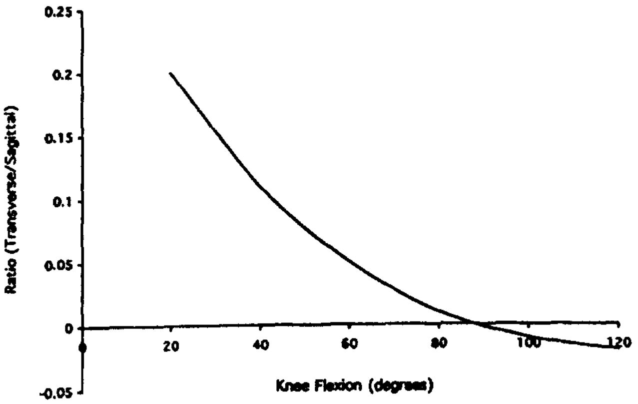

Figure 6. The PFF was resolved into mediolateral and sagittal vectors and these are expressed as a ratio. A positive value indicates that the vector was directed laterally.

Errors

To determine inter- and intraobserver errors, three observers made measurements of five additional cadaveric knees, at two flexion angles, on three separate occasions. The errors were expressed as 2 standard deviations (2SD) and were compared with the variation between different specimens (Table 2). Interobserver errors were about 50% larger than intraobserver errors. The errors in measuring force were of the order of 1% of the force magnitude. The errors were an order of magnitude less than the variation between different specimens. The errors in measuring the line of action of the PFF were about 2°.

Discussion

This new technique provides a non-invasive method to define the PFF in terms of its magnitude, direction and point of application. The compressive PFF, which is difficult to measure, is exactly replaced by a tensile force which is easy to measure. Strict criteria were applied to ensure that the tensile force exactly matched the compressive force and inter and intraobserver errors were about 1% of the actual force readings. The errors in measuring forces and angles were much smaller than the variations between different specimens, suggesting that the technique is accurate and reliable.

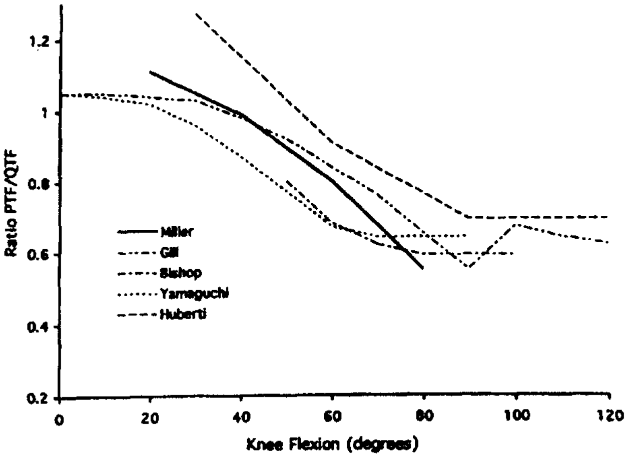

Figure 7. The ratio of the patellar tendon force (PTF) and the quadriceps tendon force (QTF) plotted against knee flexion (mean and SD). The current study is compared with previous *in vitro*[3,8] and theoretical studies[13,15].

The magnitude of the PFF

The PFF balances the resultant of the QTF and the PTF. The angle between these tendons, the patellar mechanism angle, is the major determining factor for the PFF[10,18]. Even at full extension the angle is not zero, so there will be a PFF. In our study the PFF was 75% of the QTF at 20° of knee flexion. The patellar mechanism angle steadily increases, as does the PFF, until approximately 80° of flexion, at which point the PFF, as a proportion of the quadriceps force, reaches its maximum. Beyond 80° of flexion, the quadriceps tendon begins to wrap around the distal femur and consequently there is little further change in the angle between the patellar tendon and quadriceps tendon with further increases in knee flexion[12,16]. When the quadriceps tendon wraps around the distal femur it is subjected to a substantial compressive load, the tendofemoral force, perpendicular to the line of its fibres[3,8].

Other authors have determined the PFF *in vitro*, using pressure sensitive films[2,3], electrical force transducers[4–7], and simultaneous measurement of the tensile forces in the patellar and quadriceps tendons[8–10]. Those studies that allow direct comparison[6,10,19] are presented in Figure 3a. Our results suggest that the PFF is greater at all knee flexion angles tested than do these *in vitro* studies.

The PFF has often been estimated by mathematical analysis of the geometry of the extensor mechanism. Some authors regarded the patella as a simple pulley, with the patellar tendon force equal to the quadriceps tendon force[18,20] but this premise has been contradicted by theoretical and *in vitro* studies[3,8,14]. Another approximation used in many theoretical studies was to assume a linear relationship between the patellar mechanism angle and the knee flexion angle, ignoring the effect of tendofemoral contact[18,21]. More recent analyses have taken account of these factors and,

Table 2. Inter- and intraobserver error (2 SD, $n = 45$) compared with the variation (2 SD, $n = 5$) between different specimens. The errors and variations in force magnitudes are expressed as a percentage of the magnitude. The errors and variations in angles are expressed in degrees

Measurement	Knee flexion	Intraobserver error	Interobserver error	Variation between specimens
PFF	40°	0.6%	0.9%	10.9%
	60°	0.5%	1.0%	6.2%
QTF	40°	0.8%	1.2%	16.9%
	60°	0.9%	1.3%	10.8%
PFF/QTF	40°	0.8%	1.1%	6.1%
	60°	0.9%	1.2%	11.3%
PFF angle in sagittal plane	40°	2.1°	2.5°	5.3°
	60°	2.0°	2.3°	3.3°

although they have used different mathematical methods, their results are all similar[11-13,19]. Our experimental results are in close quantitative agreement with these theoretical estimates (Figure 3b).

Direction of the PFF

Non-invasive measurement of the direction of the PFF has not been previously achieved. This is important as any disruption of the patellar retinaculae may alter the direction and point of action of the PFF. The new technique allows the sagittal and transverse components of the PFF to be deduced (Figure 6). The widely held view that the normal patella experiences significant lateral loads throughout its range of movement is not supported. We were unable to measure the lateral load at full extension, but at 20° it was only 20% of the PFF. The lateral load decreased rapidly at higher flexion angles and above 90° the load was directed medially. The lateral component of the PFF will, however, be influenced by tibial rotation[22].

The centre of pressure of the PFF

In the coronal plane, the centre of pressure was located on the lateral facet in the early stages of knee flexion but moved progressively towards the median ridge with further flexion (Figure 5). In full flexion the centre of pressure was on the medial facet; this shift occurs as the odd facet becomes loaded and the patella rotates medially about its long axis[16,23].

In our study the centre of pressure of the PFF moved proximally on the patella as the knee flexed (Figure 5b). In other words the patella rolls proximally on the femur as it slides distally. Other authors have noted the corresponding proximal migration of the patellar's contact areas with knee flexion[7,16,24,25]. We did not carry our experiment to the final stages of knee flexion and therefore cannot confirm the eventual reversal in direction of migration of the centre of pressure which has been described[11,15].

The proximal shift in the centre of pressure observed in these experiments was associated with the changing ratio of PTF to QTF. Our results are similar to previous *in vitro* studies[3,8] and theoretical analysis[13,15] (Figure 7).

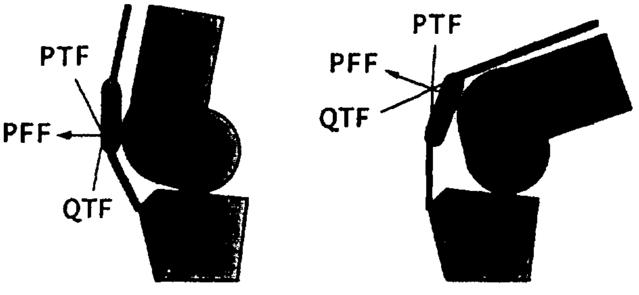

Figure 8. With knee flexion the point of intersection of the quadriceps tendon force (QTF) and patella tendon force (PTF) moves proximally relative to the patella. As a result the contact point must also move proximally.

The movement of the centre of pressure on the patella during flexion occurs not simply for geometrical reasons but also because of the mechanical requirement that the lines of action of the three forces PFF, QTF and PTF must be concurrent. As the joint flexes, the directions of the two tendons change, so that their point of intersection moves proximally (Figure 8). The contact point on the patella must also move proximally to ensure concurrence of the three forces. The patella therefore has to roll proximally on the femur during flexion and distally during extension, a requirement that implies that the patellofemoral joint has to be incongruous. The congruous patellofemoral surfaces of some total knee replacements prevent rolling if congruous contact is maintained.

Conclusion

The technique described allows the PFF to be defined fully non-invasively. It can readily be applied to specimens after arthroplasty or other surgical procedures. The study demonstrates that the PFF is higher than other more invasive cadaver studies have suggested. The lateral vector of this force was found to be small and to reduce with knee flexion.

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