The posterior cruciate ligament during flexion of the normal knee

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The posterior cruciate ligament (PCL) was imaged by MRI throughout flexion in neutral tibial rotation in six cadaver knees, which were also dissected, and in 20 unloaded and 13 loaded living (squatting) knees. The appearance of the ligament was the same in all three groups. In extension the ligament is curved concave-forwards. It is straight, fully out-to-length and approaching vertical from 60° to 120°, and curves convex-forwards over the roof of the intercondylar notch in full flexion. Throughout flexion the length of the ligament does not change, but the separations of its attachments do.

We conclude that the PCL is not loaded in the unloaded cadaver knee and therefore, since its appearance in all three groups is the same, that it is also unloaded in the living knee during flexion. The posterior fibres may be an exception in hyperextension, probably being loaded either because of posterior femoral lift-off or because of the forward curvature of the PCL. These conclusions relate only to everyday life: none may be drawn with regard to more strenuous activities such as sport or in trauma.

The attitude and tension in the posterior cruciate ligament (PCL) are not easy to determine. Even in the cadaver they are difficult to visualise without causing damage to the adjacent anatomy. Load and strain in the ligament are hard to measure. Measurements of the straight-line distance between points of attachment do not reflect the length of the PCL itself since it has a curved course. Consequently, its mechanical function during flexion in daily life is controversial.

MRI allows visualisation of the PCL in the intact cadaver and living knee.1-7 In a closed magnet the living knee cannot always be fully flexed and weight-bearing is impossible. These difficulties can be overcome by using open-access interventional machines but they have the disadvantage of weaker magnets. MRI has been validated as a method of measuring movement of the knee by comparison with roentgen stereophotogrammetric analysis/CT and three-dimensional digitisation.8

We have carried out MRI studies on cadaver and living knees and studied the appearance of the PCL throughout the range of flexion in neutral tibial rotation, both in weight-bearing and non-weight-bearing conditions. We have also dissected the cadaver knees.

Material and Methods

MR scanning. Six fresh male cadaver knees of mean age 43 years were removed at post-mortem with intact capsules (VP). As described elsewhere2,3 each knee was fixed to a wooden board with plastic pegs in full extension, and in 10°, 30°, 45°, 90° and 120° of flexion. Sagittal MRI slices, 3 mm thick, were taken in each position through the width of the knee using a Gyroscan 1.5 Tesla MRI Scanner (Philips Medical Systems, Eindhoven, The Netherlands) and a T2-weighted sequence. The knees were then re-attached to the board and the PCL examined either by removing the lateral femoral condyle or dissecting its posterior fibres.

The left knees of 20 healthy Japanese male volunteers of mean age 30 years were scanned (TK, SN) non-weight-bearing at full extension, and in 10°, 90°, 120° and full flexion (160°) in a Hitachi 0.3 Tesla, open-access machine (Airis Hitachi, Tokyo, Japan) using a T1-weighted sequence. Sagittal images 5 mm thick were taken.

Thirteen knees in 13 volunteers, 11 men and two women with a mean age of 26 years were imaged (PJ) at full extension, at 10° intervals from 0° to 120° and in full flexion (150°) during a weight-bearing squat using a 0.5 Tesla Interventional MR machine (Signa MR Imaging System; General Electrical Medical Systems, Milwaukee, Wisconsin). The pulse sequence was a fast-spoiled gradient-recalled echo in the steady state. Sagittal images of the PCL of...
5 mm thickness at full extension, 10˚, 30˚, 60˚, 90˚ and 120˚ and in full flexion (150˚) were used for this study.

All the knees in all three groups were imaged in neutral tibial rotation.

**Interpretation of the MR scans.** All MR scans were read by one observer (SN) and the locally involved workers (PJ or VP). A central point was chosen at the sites of tibial and femoral attachment (Fig. 1). The straight-line distance between these points, which is not the same as the length of the ligament since the latter may be curved, and the attitudes, i.e. angular inclinations as seen in this case in the sagittal plane, of the lines connecting them were measured in degrees relative to a line at 90˚ to the long axis of the tibia.

The distances between the sites were then expressed as a percentage of their maximum and the percentages were averaged for each group.

The length of the PCL at full extension and at 10˚, 30˚, 45˚, 90˚ and 120˚ was measured twice by one observer (SN) on the six cadaver MR scans. The images were magnified to twice life-size. A strip of modelling material was fitted to the posterior border of the ligament. This was then removed from the MR scan without altering its length and then straightened and measured, adjusting for scale. The lengths were averaged. To determine the error of the method, a piece of clay 10 cm in length was photographed at three curvatures and the images were measured, as were the MR scans. The maximum error was 2%.

**Dissection of the cadaver knees.** Two types of dissection were carried out. Either the lateral femoral condyle was removed with the knee attached to the board to expose the ligament from the side or the posterior fibres were dissected.

**Statistical analysis.** The distance between the sites of attachment and the angular attitudes were analysed using one-factor ANOVA and the Bonferrini/Dunn test to compare the difference in the three groups at full extension and in 10˚, 90˚ and 120˚ of flexion. The t-test was used to compare the difference between groups of cadaver and loaded living knees at 30˚ because of the lack of data in unloaded living knees at this angle. The difference between each angle of flexion in the same group was calculated by a paired t-test. A p value of less than 0.05 was deemed to be significant.

**Results**

**MRI findings.** The typical appearance of the PCL in the cadaver is shown in Figure 1. The white square on the 10˚ image represents the location of the 0˚ to 10˚ helical axis. The location of the flexion axis over the arc of 30˚ to 120˚ is shown by the white squares at 30˚, 45˚, 90˚ and 120˚. The appearance of the ligament changed over the range of movement in the same way in all the living and
cadaver knees examined (Figs 2 to 4) and is described in the discussion.

The measured lengths (Table I and Fig. 5) of the cadaver images are greater than in the living knees, although significantly only at full extension and 120°, probably because of the better image quality produced by the use of a more powerful magnet. The separation of the attachments of the PCL was the least at full extension (Fig. 5). It was maximal at 90° for unloaded living knees and at 120° for cadaver and loaded living knees. At full extension the separation between the attachments of the PCL was shortened by 20.5% in cadaver knees, by 22.5% in unloaded knees and by 23.7% in loaded knees compared with its maximum separation.

At 90° the PCL was inclined 63.7° in cadaver knees, 65.9° in unloaded and 65.0° in loaded knees (Figs 1 to 5, Table II). It was at its most horizontal at full extension in the cadaver and loaded living knees and at 10° in unloaded knees, but
there was no significant difference between -5° and 10° in unloaded knees; paired t-test, p = 0.0843). Thus the ligament became more vertical with flexion with similar attitudes in the three groups.

The length of the PCL at the six angles of flexion measured in each cadaver knee varied over a small range. Taking the shortest image to be 100%, the longest ranged from 101% (+ 0.5 mm) to 104% (+ 2.0 mm). Neither the shortest nor the longest image occur regularly at the same angle. The longest image was measured at 45° of flexion in three knees, at 120° in two and at both 30° and 90° in one. Thus, the measured increase in the length of the image was not constant, small and did not correlate with the increased straight-line separation between the attachments. In part, it probably represented the error of the method (2%).

Findings on dissection. In all cadaver specimens no resistance to passive movement of the knee was felt except at full extension and at 120°. After removal of the lateral femoral condyle the appearance of the ligament at full extension and at 90° as seen from the lateral side was the same as on the MRI scan (Fig. 6). At full extension, traction with a tape demonstrated that the PCL was slightly slack (Fig. 6).

In the second dissection, the knee was stressed into full extension, the posterior capsule was removed and the PCL palpated; it felt ‘firm’ as it curved over the medial tibial spine. The ligament was not differentiated into separate bands. Some fibres were then separated from the posterior part of the ligament by sharp dissection in its long axis, painted with green water-colour paint to facilitate visibility for photography and divided transversely. The cut ends sprang 2 to 3 mm apart (Fig. 7a). The knee was then flexed to 10° whereupon the gap in the artificially separated posterior fibres closed (Fig. 7b). We interpreted these findings as showing that some posterior fibres were tense at full extension but not at 10°.

Discussion

The appearance of the PCL from 0° to 90° on MRI in the intact, unloaded cadaver knee\textsuperscript{2,6} and in the unloaded living knee has been described previously and is similar to that described here. We have studied the PCL only in neutral tibial rotation and therefore its role in tibial rotation both during flexion and in isolation is outside the scope of this paper.

Table I. The mean separation of the PCL attachments measured as the straight-line distance between the centres of the tibial and femoral attachment areas (mm)

<table>
<thead>
<tr>
<th>Flexion angle (degrees)</th>
<th>Full extension</th>
<th>10</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadaver knees</td>
<td>38.4* **</td>
<td>39.7</td>
<td>40.8</td>
<td>45.4</td>
<td>-</td>
<td>47.4</td>
<td>48.3***</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Unloaded living knees</td>
<td>33.7*</td>
<td>37.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>43.5</td>
<td>41.9***</td>
<td>-</td>
<td>39.6</td>
</tr>
<tr>
<td>Loaded living knees</td>
<td>33.5**</td>
<td>35.9</td>
<td>36.6</td>
<td>-</td>
<td>41.3</td>
<td>43.0</td>
<td>43.9</td>
<td>40.8</td>
<td>-</td>
</tr>
<tr>
<td>* ** ***; p&lt;0.05</td>
<td></td>
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Table II. The mean attitude of the PCL in degrees relative to the horizontal

<table>
<thead>
<tr>
<th>Flexion angle (degrees)</th>
<th>Full extension</th>
<th>10</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadaver knees</td>
<td>46.5</td>
<td>49.2</td>
<td>52.0</td>
<td>56.2</td>
<td>-</td>
<td>63.7</td>
<td>75.2**</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Unloaded living knees</td>
<td>50.6*</td>
<td>48.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>65.9</td>
<td>86.2**,** ***</td>
<td>113.0</td>
<td>-</td>
</tr>
<tr>
<td>Loaded living knees</td>
<td>46.2*</td>
<td>48.3</td>
<td>52.1</td>
<td>-</td>
<td>56.8</td>
<td>65.0</td>
<td>75.5***</td>
<td>100.3</td>
<td>-</td>
</tr>
<tr>
<td>Mean</td>
<td>48.5</td>
<td>48.6</td>
<td>52.1</td>
<td>56.2</td>
<td>56.8</td>
<td>65.3</td>
<td>80.9</td>
<td>100.3</td>
<td>113.0</td>
</tr>
<tr>
<td>* ** ***; p&lt;0.05</td>
<td></td>
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Fig. 6

Dissections at full extension (-5°) and 90° (from Iwaki et al\textsuperscript{6} reproduced by permission of Oxford University Press). The PCL is relaxed at full extension but straight and tense at 90°. A tape round the PCL at full extension shows that the ligament can be deflected by slight traction.
The distal half of the ligament, posterior to the tibia, did not change in attitude throughout the range in all three groups studied except in full flexion when it rotated backwards to a slight extent away from the tibia (Fig. 4). Above the tibial tubercle the ligament curved strongly forwards in extension over the intercondylar eminence and appeared to be relaxed. As flexion progressed the femoral attachment moved upwards and backwards, straightening the ligament and separating its attachments. Finally, at full flexion, the curvature of the PCL reversed apparently because of impingement against the proximal aspect of the roof of the intercondylar notch. This was seen only in the living knee since the cadaver joints were not imaged in full flexion. These changes in separation of the attachments and attitude did not result in a change in the length of the ligament itself which merely varied between being curved or straight. The changes can be explained as being due to rotation of the femoral attachment of the ligament around the flexion axis combined with posterior translation of the midline of the femur caused by the longitudinal rotation around a medial axis which accompanies flexion.\textsuperscript{2,3} Since the movement of the medial condyles is the same in the cadaver and living knees, with and without weight-bearing,\textsuperscript{4,7} this explanation would apply to all of the three groups.

Wascher et al\textsuperscript{9} and Markolf et al\textsuperscript{10} measured the load in the PCL from 0˚ to 90˚ in the unloaded cadaver knee. In the absence of applied anteroposterior forces and torques there was a force in the PCL of about 10 N, which is approximately equivalent to a weight on the ligament of 1 kg, in a minority of knees at full hyperextension, an immeasurably small load between 0˚ and 30˚, and then a gradual rise to about 5 N at 90˚ in most, but not all, knees. Thus, the forces were small, inconstant and were found only in hyperextension and towards 90˚.

We could not measure the load on the PCL but we could determine its extension on cadaver MR scans. The 25% extension of the linear separation of the areas of attachment which we observed with flexion of the cadaver knee may have been due theoretically either to strain, to straightening of a curved ligament or to a mixture of both. The effect of strain is unlikely in view of the demonstration of a lack of load in the ligament by Markolf et al\textsuperscript{10} and of the finding by Kennedy et al\textsuperscript{11} that the ligament yields at a strain of 20%. Our measurements of the cadaver PCL image show that true changes in length, if they occur, average no more than 2%. Even then the increase in true length is not related to flexion in the same way in each knee and is not correlated with linear separation. We suspect therefore that this variation is inherent in the method, not in the ligament itself. We conclude that as the knee flexes the PCL changes in curvature but not in length. Therefore, it does not undergo strain and hence we agree with Markolf et al that the ligament is not materially loaded during flexion of the unloaded cadaver knee.

Notwithstanding this conclusion as to the PCL as a whole, the tension in different groups of fibres has been said to vary with the angle of flexion. Fuss\textsuperscript{12} separated the ligament by sharp dissection into ten ‘artificial bundles’ of varying attachments and reported his findings in relation to those in the literature up to 1975. Two further studies have been undertaken since then.\textsuperscript{13,14} Since there are no separate bundles in the natural ligament, none was seen in our MR scans and in our dissections. Thus, we have no measurements relating to the possible separate function of artificially created groups of fibres in the ligament except posteriorly. However, so marked is the curvature of the ligament at certain angles of flexion that it is difficult to see how individual fibres within it could be under tension if the ligament as a whole was not.
It has been found that the relative movements of the medial condyles are the same in flexion in the living unloaded knee and when squatting as in the unloaded cadaver knee. We believe that the attitude and separations of attachments of the PCL during flexion can be explained as being due to the relative movements of the femur and tibia and therefore expect that the behaviour of the PCL is the same in the three groups studied. Our observations have confirmed this. The appearance of the PCL during flexion was unchanged by weight-bearing and in the cadavers. Since the PCL in the unloaded cadaver knee is itself unloaded, it follows that the ligament is not loaded during a weight-bearing squat in the living knee, except possibly initially in hyperextension. This conclusion is similar to that of Blacharski, Somerset and Murray who stated that “the action of the cruciates is minor and is only noticeable near the extremes”. This view does not imply that the PCL would not be loaded by anteroposterior forces or by torque applied to the tibia. It has been shown experimentally that the ligament is loaded by such forces and that these may well occur during sports or injury.

Hyperextension remains to be considered. At hyperextension, but not at 0°, Wäscher et al and Markolf et al found a small load in the PCL and Kurosawa et al found separation between the attachments of the posterior fibres. Girgis, Marshall and Al Monajem and Fuss also reported that the posterior fibres were tight in extension. Our experiment in which we cut some posterior fibres confirms that these fibres were under load in hyperextension, but this experiment and that illustrated in Figure 6 suggest that the fibres were unloaded at 10° and 0°. There are two possible explanations for these findings. First, it has been noted that in hyperextension the posterior femoral condyles lift away from the tibia. This separation may tighten the posterior fibres of the PCL. Also, since the PCL feels ‘firm’ and its posterior fibres are under tension in hyperextension, this may be due to flexion of the PCL over the tibial spine (Figs 1 to 4). On the analogy of a flexed rope, the posterior, convex fibres may be under tension even though the ligament as a whole is not carrying a load while the sense of firmness may be due to palpation of the tibial spine deep to the ligament.

Our observations suggest that throughout the range of flexion in neutral tibial rotation during the non-athletic activities of daily life, the PCL is under little or no tension and does not change in length. When the straight-line separation between its attachments is at a maximum, the ligament is straight and ‘out-to-length’. When the separation is reduced, the PCL becomes curved. At or near full extension the curvature is concave-forwards over the tibial eminence and at or near full flexion the curvature is concave-backwards over the posterior end of the roof of the femoral intercondylar notch.

Although we believe that the PCL is not under tension and therefore may not be required to prevent anterior femoral subluxation during non-athletic flexion, it could read-


