In 13 unloaded living knees we confirmed the findings previously obtained in the unloaded cadaver knee during flexion and external rotation/internal rotation using MRI. In seven loaded living knees with the subjects squatting, the relative tibiofemoral movements were similar to those in the unloaded knee except that the medial femoral condyle tended to move about 4 mm forwards with flexion.

Four of the seven loaded knees were studied during flexion in external and internal rotation. As predicted, flexion (squatting) with the tibia in external rotation suppressed the internal rotation of the tibia which had been observed during unloaded flexion.

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The aims of this study were to determine if the living knee could be imaged in a clinically practicable fashion in the same way as the cadaver knee\(^1\) and whether tibiofemoral motion in the living unloaded knee was the same as that in the unloaded cadaver. We then examined the effect of load applied either externally as a tibial torque or by weight-bearing and muscle action with and without tibial longitudinal rotation during flexion in the living knee.

Subjects and Methods

Two groups of volunteers were recruited in the Royal Hospital Haslar, Gosport (hospital A: six knees; five male, aged 21 to 32 years) and in St Mary’s Hospital, London (hospital B: seven knees; seven male, aged 22 to 35 years). All the knees were normal and the volunteers Caucasian. Table I gives the details.

Hospital A. Images during unloaded flexion were acquired using a Picker Outlook 0.23 Tesla Open Access MRI scanner (Picker International Inc, Cleveland, Ohio). A wooden template, which allowed accurate positioning of the knee in various degrees of flexion, was slotted into the scanner couch. The volunteer lay on the template in the lateral position with the knee to be scanned lowermost. The receiver coil was placed around the knee so that it overlaid the femoral condyles. The thigh was held by Velcro straps and a wooden peg was placed behind the popliteal fossa to prevent movement of the femur during flexion.

The following images were obtained: four sagittal slices of 10 mm thickness with a 15 mm gap between cuts at -5° (quadriceps contracting), 10°, 40°, 50°, 90°, 90° (plus flexion against resistance), 90° (plus extension against resistance) and 110°, and 22 slices of 3 mm thickness centred on the intercondylar notch at 0° (quadriceps relaxed), 30°, 60° and 90°. This examination, with a practised radiographer, required about 40 minutes.

A template was made by tracing images of the sagittal sections of the lateral and medial tibial condyles from the first scan. This was then overlaid on the monitor to ensure that the same point on the tibia was being scanned each time.

Hospital B. MR images were obtained as previously described by Vedi et al.\(^2\) With the volunteer seated, non-weight-bearing images at -5°, 10°, 45° and 90° were obtained with the foot supported by an examiner. At 90°, the knee was then rotated into tibial external rotation (ER) and internal rotation (IR) and an anteroposterior (AP) drawer test was carried out. The configuration of the machine made it difficult to apply adequate AP force and stabilise the foot at the same time. The knee was therefore often stressed inadequately and at less than 90°.

Weight-bearing MR images were obtained as follows. Seven subjects stood leaning against a board angled backwards by 10°. Four positions were imaged, namely, full extension with the quadriceps contracting maximally, and squats maintained by isometric muscle contraction at 10°, 45° and 90°. Each of these sequences was carried out in three rotational positions. In the first, all seven subjects stood with their feet in a comfortable rotational position (here called ‘neutral rotation’). In the second (IR in the text and diagrams) four of the seven stood with the hips fully...
internally rotated and with the toes in contact. In the third, in the same four subjects, the hips were fully externally rotated with the heels and knees in contact. In each of the positions of rotation the position of the feet did not move as the subject squatted. Thus what had been full IR or ER of the hip in extension became the corresponding rotation of the tibia on the femur in the flexed knee. The MR images were measured as previously described by two observers (HI and VP or VV).

Results

Flexion in the unloaded knee (Fig. 1). Medially, the mean AP position of the femoral condyle did not change from 110° to -5°. The position of the condyles as judged by their posterior centres over the arc -5° to 30° should be adjusted by a maximum of 2 mm to allow for the fact that rotation during this arc is around the centre of the anterior femoral surface. Hence this section of the graph in Figure 1 is dotted.

Laterally, the femoral condyle rolled forwards from 110° to 60°, a total of 13 mm, corresponding to 15° of femoral IR (tibial ER) as the knee extended. There was then 1 mm of forward femoral movement, equivalent to 1° of rotation, from 60° to 0°. Finally, the condyle again moved forward 3 mm as the femur internally rotated 4° to ‘screw home’. Passive rotation of the tibia at 90° (Fig. 2). IR of the tibia caused the medial femoral condyle to move forwards relative to the tibia and ER to move it backwards by about the same distance in the living and cadaver knees. In both, the axis of rotation appeared to lie about 15 mm lateral to the medial condylar midline, at about the femoral attachment of the posterior cruciate ligament. Laterally, ER of the tibia caused the femur to move forwards to an extent sufficient to reverse the posterior displacement which accompanied flexion to 90° in the cadaver, and more than reverse this in the living knee. IR of the tibia caused the opposite displacement laterally but to a slightly more anterior point and through a greater angle (26° v 17°) than in the cadaver.

Squatting (Fig. 3). The mean results in IR and ER are based on only four knees.

The behaviour of the knee in neutral and in IR (Figs 3a and 3b) was essentially the same. The medial femoral condyle moved about 4 mm forward before 10° flexion in neutral tibial rotation and after 10° in tibial IR. The lateral condyle moved backwards to a greater extent than in the absence of load. Thus, as in the loaded knee, flexion was accompanied by ER of the femur on the fixed foot but the arc of rotation was greater than in the absence of load.

When squatting with the tibia in ER neither condyle

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Table I. Details of the subjects and dimensional data

<table>
<thead>
<tr>
<th></th>
<th>Hospital A</th>
<th>Hospital B</th>
<th>Cadaver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male:female</td>
<td>5:1</td>
<td>7:0*</td>
<td>6:0</td>
</tr>
<tr>
<td>Mean age in years (range)</td>
<td>24.5 (21 to 32)</td>
<td>27.4 (22 to 35)</td>
<td>43 (25 to 55)</td>
</tr>
<tr>
<td>Left:right</td>
<td>0:6</td>
<td>0:7</td>
<td>1:5</td>
</tr>
<tr>
<td>Pathology</td>
<td>Absent</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>Slice separation (mm)†</td>
<td>43.2</td>
<td>48.5</td>
<td>46.6</td>
</tr>
<tr>
<td>AP level of medial v lateral posterior tibial cortex (mm)†</td>
<td>7.5</td>
<td>8.4</td>
<td>5.9</td>
</tr>
<tr>
<td>Length of tibial condyle (mm)</td>
<td>58</td>
<td>58</td>
<td>51</td>
</tr>
<tr>
<td>Medial</td>
<td>51</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* data for squatting with axial rotation were obtained in only four of these knees
† averaged to 46 mm and 7 mm in the diagrams in this study
moved anteroposteriorly. Thus the knee flexed from -5° to 90° as if it were a uniaxial hinge (Fig. 3c).

**Isometric muscle contraction at 90°.** The medial condyle did not move anteroposteriorly during contraction of the quadriceps or hamstrings. During contraction of the hamstrings the lateral tibial condyle moved posteriorly 2 mm, i.e., the tibia rotated externally. Thus a static contraction of the hamstrings at 90° causes the tibia to rotate externally around a medial axis. We attribute this to the AP stability of the medial compartment combined with translational freedom laterally. Similar external tibial rotation in response to a simulated hamstring contraction has been reported in the cadaver.\(^3,4\)

**AP drawer sign.** The knee could not be adequately flexed or stressed in the seated position in which this test was carried out. Thus the displacements of 2 mm of translation medially and 3 mm laterally which were observed may be an underestimate.

**‘Lift-off’ of the flexion facets (FFs).** As the knee extends, femoral contact with the tibia in the cadaver knee has been found to transfer forwards from the FF to the extension facet (EF) causing the FFCs to rise.\(^1\) In this study the centres of the FFs also rose relative to the tibia in non-weight-bearing knees, by 2.6 mm (hospital A) and 1.9 mm (hospital B) medially and 1.25 mm (hospital A) and 0.9 mm (hospital B) laterally between 10° and -5° flexion. In the weight-bearing knee (hospital B), the values were 2.7 mm medially and 1.1 mm laterally. Maximal contraction of the quadriceps reduced the lift-off (in hospital A) by 1.3 mm on both sides.

Thus, in living knees, as in the cadaver, tibiofemoral contact transfers from a posterior (‘flexion’) facet to an anterior (‘extension’) facet at about 20° irrespective of whether the knee is weight-bearing or not.

**Conclusions**

The method by which tibiofemoral motion has been imaged and measured in the cadaver knee\(^1\) can be applied to the living knee and the latter can be imaged in a clinically reasonable period of time as found by others.\(^3,5\) Tibiofemoral motion in the unloaded living knee when reclining or seated, is the same as that in the cadaver.

When load is applied as statically maintained flexion on the weight-bearing knee it alters tibiofemoral motion in neutral tibial longitudinal rotation. The medial femoral condyle translates forwards about 4 mm between 10° and 45° flexion and the lateral femoral condyle moves backwards further than in the absence of load. Isometric muscle contraction and externally applied AP force also produce small displacements.

The pattern of motion accompanying flexion varies with associated tibial longitudinal rotation. External rotation of the tibia suppressed the internal rotation which otherwise accompanied flexion at least as far as 90°. Consequently, the knee flexed as would a hinge, without axial rotation.

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No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

**References**


A list of consulted publications concerning the normal knee will be found on the *Journal of Bone and Joint Surgery* web site (www.jbjs.org.uk) for this issue until 2002.