The effect of trochleoplasty on patellar stability and kinematics

A BIOMECHANICAL STUDY IN VITRO

A. A. Amis, C. Oguz, A. M. J. Bull, W. Senavongse, D. Dejour

From Imperial College London, London, England

Objective patellar instability has been correlated with dysplasia of the femoral trochlea. This in vitro study tested the hypothesis that trochleoplasty would increase patellar stability and normalise the kinematics of a knee with a dysplastic trochlea. Six fresh-frozen knees were loaded via the heads of the quadriceps. The patella was displaced 10 mm laterally and the displacing force was measured from 0° to 90° of flexion. Patellar tracking was measured from 0° to 130° of knee flexion using magnetic sensors. These tests were repeated after raising the central anterior trochlea to simulate dysplasia, and repeated again after performing a trochleoplasty on each specimen. The simulated dysplasia significantly reduced stability from that of the normal knee (p < 0.001). Trochleoplasty significantly increased the stability (p < 0.001), so that it did not then differ significantly from the normal knee (p = 0.244). There were small but statistically significant changes in patellar tracking (p < 0.001).

This study has provided objective biomechanical data to support the use of trochleoplasty in the treatment of patellar instability associated with femoral trochlear dysplasia.

Many anatomical and physiological factors such as limb malalignment, unbalanced muscle actions, damaged retinacular restraints and abnormal joint geometry have been linked to problems of patellar instability or maltracking. The range of disorders has led to a correspondingly wide variety of surgical procedures intended to correct these abnormalities. These operations have addressed the soft tissues, such as lateral retinacular releases, and hard tissues, such as medialisation of the tibial tuberosity. However, these procedures are sometimes insufficient, particularly in the face of a skeletal abnormality.

Among the bony abnormalities, dysplasia of the femoral trochlea has been found to correlate most strongly with objective patellar instability. An abnormally large sulcus angle is the most common finding in patellar malalignment, and the proximal trochlear groove is significantly less deep in knees with recurrent dislocation. The proximal-lateral trochlea is convex in ‘skyline’ cross-section. This convexity extends twice as far around the flexion arc in patients with unstable patellae as in controls, reflecting a filling-in of the proximal groove in unstable knees. From a mechanical viewpoint, it is logical to expect that the slope of the lateral facet of the femoral trochlea will be an important factor in resisting the lateral force vector acting on the patella as a result of the ‘Q’ angle between the resultant force of the quadriceps and of the patellar tendon. The nature of the changes in trochlear geometry in dysplasia have been more widely understood recently. It was formerly believed that the lateral edge of the trochlea had been depressed, leading to the Albee procedure, which raises the lateral edge of the articulation. However, that procedure can cause ‘lateral patellofemoral impingement’. It is now recognised that the mediolateral flattening of the anterior surface of the trochlea results principally from an excess of material centrally. This may form a supratrochlear eminence or bump anterior to the shaft of the femur, which the patella has to surmount when the knee starts to flex. This central mass results at least partly from the articular cartilage being much thicker centrally than at the edges of the trochlea, exaggerating the normal thickness distribution. The degree of geometrical abnormality has been graded, and these gradations have been correlated with changes observed on the lateral radiographs. When the trochlea is normal, the shadow of the base of the groove remains below that of the edges of the trochlea. In a dysplastic trochlea, a ‘crossing sign’ is seen when the base of the groove...
becomes as high as the lateral edge of the trochlea. This indicates that the anterior trochlea is flat mediolaterally. These observations suggest that a trochleoplasty which deepens the central trochlea to form a groove is a logical procedure in order to provide a stable pathway for the patella.

However, trochleoplasty is not undertaken widely, despite the recent appreciation of the abnormal geometry. One reason may be that surgeons fear the consequences if the procedure leads to necrosis of the osteochondral shell, but this has not been the experience of centres which have used the procedure, and histological evidence showing viable cartilage from clinical cases has been published. A further possible reason is the absence of any published biomechanical evidence of its efficacy. The objective of this paper, therefore, was to study the effect of trochleoplasty on patellar tracking and lateral stability. We hypothesised that a joint with a dysplastic trochlea would be significantly less stable than a normal knee, and that the patella would track further laterally than normal. We also considered that a trochleoplasty would cause the patella to become significantly more stable than when articulating in a dysplastic trochlea, and that it would cause the patella to take a more medial track during flexion and extension of the knee.

Materials and Methods

Preparation of the specimens. In order to make comparisons between normal, dysplastic and post-trochleoplasty states, this study was performed in vitro. A total of six normal knees were obtained post mortem, with approval of the ethical committee and informed consent from relatives. The specimens were approximately 18 cm long above and below the joint line, and complete with all soft tissues deep to the subcutaneous fat. The specimens were sealed in polyethylene bags and stored at -20°C before use, when they were thawed to room temperature. They were prepared and the muscles were loaded using an accepted method. All the muscles were excised, apart from the quadriceps. Care was taken to keep all capsular and retinacular tissues intact. Both the femur and the tibia were extended by 15 cm by the insertion of intramedullary rods secured to the bone using polymethylmethacrylate cement. The fibula was secured in an anatomical position using a transverse screw that passed through it into the tibia. The components of the quadriceps muscle were separated from each other, starting proximally, including the oblique parts of the vasti lateralis (VLO) and medialis (VMO). The vastus intermedius (VI) was elevated from the femur. The proximal ends of the muscles were bound with cloth tapes, secured by suturing through the muscle. This provided anchorages for attaching cables, to tense the muscles. The rectus femoris (RF) was sutured to the VI proximally, to act in the same direction. The long heads of the vasti medialis (VML) and lateralis (VLL) were detached from their origins, working distally until the muscles could be folded over anteriorly, to allow access to the trochlea while keeping the retinacula intact. This preparation created the ‘normal’ condition for the knee.

Measurement of patellar stability. This was measured objectively by examining the force required to displace the centre of the patella 10 mm laterally. This method has been described previously. In order to apply the displacing force and not influence patellar tilting, a spherical ball bearing 10 mm in diameter was mounted in the patella. A hole was drilled at the centre of the anterior aspect of the patella, and the bearing housing cemented in place so that the ball was 10 mm below the anterior surface. The femoral intramedullary rod was secured in a stationary fixture on the base of an Instron 1122 materials testing machine (Instron Ltd, High Wycombe, United Kingdom). The knee was orientated with the lateral aspect uppermost, so that the tibia flexed in a horizontal arc. A total load of 175 N was applied to the muscle groups by hanging fixed weights according to the directions and physiological cross-sectional areas of the muscles relative to the femoral axis:

- VLO 35° lateral and 33° posterior;
- VLL 14° lateral and 0° anterior;
- RF+VI 0° lateral and 0° anterior;
- VML 15° medial and 0° anterior;
- VMO 47° medial and 44° posterior (Fig. 1).

The quadriceps tension distribution was: VLO 9%, VLL 33%, RF+VI 35%, VML 14% and VMO 9%.

In order to displace the patella laterally, a rig with three degrees-of-freedom was mounted onto the load cell at the moving crosshead. The three degrees of freedom were flexion-extension rotation and anteroposterior plus proximal-distal translations in the sagittal plane. These allowed the patella to climb uphill as it was displaced laterally out of the patellar groove, and to move when the knee was flexed. The rig was connected to the ball-bearing in the patella, which therefore had five degrees-of-freedom of movement, plus imposed mediolateral displacements.

Patellar stability was defined by measuring the force needed to reach 10 mm of lateral displacement from its resting position. This was measured at 0°, 10°, 20°, 30°, 45°, 60° and 90° of knee flexion. A transverse rod held the tibia at the desired angle of flexion against the extending action of the quadriceps tension while the patella was being displaced.

Kinematic measurement. The kinematics of the patella in relation to the femur was measured using the ‘Flock of birds’ electromagnetic system (Ascension Technology, Burlington, Vermont) as previously described. The accuracy of this system has been validated and found to be SD 0.1 mm in a 50 mm translation and SD 0.5° in a 25° rotation. A magnetic sensor was mounted on the superficial surface of the patella via an interposed perspex plate, which was secured using two 15 mm bone screws. The specimen was fixed into a wooden (non-magnetic) test fixture via the femoral intramedullary rod. The magnetic source transmitter was mounted onto the same fixture. The alignment of the specimen mounting to the magnetic transmitter gave data on patellar movement related directly to the fixed femoral axis (Fig. 2). A second magnetic sensor was mounted on the tibia to measure knee flexion. Cables were attached to each muscle component, and led over pulleys to hanging weights, as before.
Patellar tracking was measured while the knee was flexed and extended through an arc of approximately 130°. The investigator pushed the knee into flexion against the quadriceps action, using a transverse rod pressed against the tibial intramedullary rod. This method did not inhibit secondary tibial movement. Relaxation of the flexing force allowed the quadriceps to extend the knee, with each movement cycle taking approximately six seconds. Data were collected for ten movement cycles.

Simulation of trochlear dysplasia. After the ‘normal’ patellar kinematics and stability had been measured the knee was modified to simulate trochlear dysplasia. A transverse slot was cut across the proximal edge of the trochlear articular surface. Fine bone nibblers and a slim osteotome were used to undermine the anterior trochlea, working distally to create an osteochondral shell secured to the femur distally and at its medial and lateral margins. This shell was elevated centrally and the underlying cavity packed with bone fragments and bone cement, until the anterior surface was flat across its width. The proximal step that this caused was smoothed using bone cement, which formed a slope from the anterior femur. The senior surgical author (DD) confirmed that this gave a joint geometry that was a good approximation to the shape found in severe trochlear dysplasia, which conformed exactly to published descriptions⁶,¹⁵ (Fig. 3). The patellar geometry was not modified. The resulting ‘dysplastic’ knee was then subjected to the same patellar tracking and stability testing as before.
Trochleoplasty. This procedure was similar to that described by Dejour et al., Verdonk et al. and Donell et al. The dysplastic trochlea was undermined from the proximal approach as described above, leaving a thin osteochondral shell. The cavity extended further centrally, leaving a shield-shaped shell unsupported. The proximal centre line was then cut, and medial and lateral trochlear facets were re-formed by pressing the centre of the shell down and securing the osteochondral flaps to the underlying bone with small bone screws. The effect of the trochleoplasty was then found by repeating all the stability and tracking measurements.

Data analysis. Stability and tracking parameters were compared between the three states of the trochlea using repeated-measures two-way analyses of variance (ANOVA) with Bonferroni post-testing for significant differences at specific angles of knee flexion. An α level of 5% was assumed for significance.

Results

Lateral stability. For the normal knee, 10 mm lateral displacement of the patella required a mean force of 78 N (SD 8) at 0° knee flexion. This fell to a mean minimum of 67 N (SD 14) at 20°, then rose to a mean force of 112 N (SD 21) at 90° flexion (Table I and Fig. 4).

With trochlear dysplasia, the mean force for 10 mm lateral displacement was 57 N (SD 16) at 0° knee flexion, representing a 27% reduction from normal. The displacing force fell to a mean minimum of 40 N (SD 11.0) at 30° flexion (49% reduction), then rose to a mean of 90 N (SD 19.0) at 90° flexion (20% reduction) (Table I). ANOVA showed that, overall, the dysplasia reduced patellar lateral translation stability significantly (p < 0.001).

After trochleoplasty the mean force needed to displace the patella 10 mm laterally was 74 N (SD 14) at 0° knee flexion. This force rose progressively with knee flexion, to a mean of 116 N (SD 26) at 90° flexion. ANOVA showed that, overall, the trochleoplasty increased patellar stability significantly (p < 0.001). After the trochleoplasty, the knees did not differ significantly from normal (ANOVA p = 0.244).

Patellar kinematics. The mean patellar mediolateral tracking movement for all three states of the knee (normal intact, dysplastic, post-trochleoplasty) was a progressive lateral translation with knee flexion (Fig. 5). ANOVA found that there was a significant overall effect on patellar lateral displacement between the three states of the trochlea (p < 0.001), but post-testing did not demonstrate specific significant differences with: p > 0.05 for all post-tests apart from the difference between the dysplastic and the post-trochleoplasty states at 0° knee flexion (p < 0.05). We observed that the patellae in the simulated dysplastic knees tended to translate medially when extended beyond approximately 20° flexion.

Discussion

This study has provided the first objective evidence of the mechanical effects of a simulated trochlear dysplasia, and of trochleoplasty, on the lateral stability and kinematics of the patellar. As anticipated, compared with the normal knee, the simulated trochlear dysplasia led to a significant reduction in

<table>
<thead>
<tr>
<th>Knee flexion (°)</th>
<th>Normal intact</th>
<th>Dysplastic</th>
<th>Post-trochleoplasty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>p-value vs trochleoplasty</td>
</tr>
<tr>
<td>0</td>
<td>78.0</td>
<td>8.0</td>
<td>NS†</td>
</tr>
<tr>
<td>10</td>
<td>71.0</td>
<td>9.0</td>
<td>NS</td>
</tr>
<tr>
<td>20</td>
<td>67.0</td>
<td>14.0</td>
<td>NS</td>
</tr>
<tr>
<td>30</td>
<td>78.0</td>
<td>15.0</td>
<td>NS</td>
</tr>
<tr>
<td>45</td>
<td>90.0</td>
<td>18.0</td>
<td>NS</td>
</tr>
<tr>
<td>60</td>
<td>102.0</td>
<td>18.0</td>
<td>NS</td>
</tr>
<tr>
<td>90</td>
<td>112.0</td>
<td>21.0</td>
<td>NS</td>
</tr>
</tbody>
</table>

* all p-values were derived using Bonferroni post-tests
† NS, not significant
By reconstituting a deep femoral trochlear groove, the trochleoplasty increased this so that it did not then differ significantly from the intact knee. In this simulation a trochleoplasty provided a powerful means for stabilising the patella against lateral displacement.

Patellar instability, maltracking, or symptoms of excessive contact pressure on the lateral facet are relatively common, and have led to many surgical procedures intended to correct them. However, there have been very few objective data with which to compare the efficacy of the different operations. The role of the slope of the lateral facet of the trochlea in resisting lateral translation of the patella is well accepted. Other in vitro work has shown that flattening the lateral trochlea caused a greater loss of patellar stability than dysfunction of vastus medialis obliquus or rupture of the medial retinaculum across most of the arc of knee flexion. It was also found that the medial retinacular tissues were the most important factor in lateral stability when the knee was extended. The changes in the trochlea in the present study did not cause significant changes in patellar lateral stability at 0° flexion, reflecting the earlier results.

Although these experiments demonstrated that the geometry of a dysplastic trochlea caused the patella to become significantly less stable against laterally displacing forces, and that trochleoplasty produced a significant restoration of stability, we noted that the patellae in dysplastic knees tended to move medially as the knee extended, compared with normal intact behaviour (Fig. 5). This might have resulted from tightening of the medial retinacular restraints as a consequence of the patella being elevated anteriorly by the dysplastic geometry in these otherwise normal experimental specimens.

We are not aware of any previous work that has provided objective data on the stability or kinematics of the dysplastic patellofemoral joint, nor of trochleoplasty. The stability characteristics of the normal joints in this study were in line with those observed previously using the in vitro loading and movement protocols, and the tracking data also fit with previous studies. In general, the results of this study were as expected, based on the simple observation that it is more difficult to push an object (the patella) up a hill (the normal lateral facet of the femoral trochlea) than is to push it on the flat (the dysplastic geometry).

There are limitations to an in vitro study, but this seemed to be the only way to obtain detailed comparative measurements of the three states of the knee (normal and intact, dysplastic and post-trochleoplasty) across the range of knee flexion. We have been unable to obtain dysplastic knees post mortem and so do not know the accuracy of the model of simulated dysplasia. We realise that, if the geometry of the trochlea is abnormal, so might other factors. We loaded the different parts of the quadriceps according to data from normal legs and decided to leave the patella unaltered. This meant that the medial patellar facet lifted off the trochlear surface with the simulated dysplasia, because the abnormal geometry was effectively flat in a mediolateral direction, a situation akin to that described by Wiberg. It has been found that patellar geometry changes in clinical cases of trochlear dysplasia, having a distal medial facet that is smaller than normal and which does not articulate with the trochlea. This is mechanically similar to the model used in this experiment. We felt that this was the most appropriate method to use, because it did not affect the engagement of the lateral patellar facet with the trochlea, which is the principal determinant of lateral stability.

Although this in vitro model undoubtedly lacks all the features of the pathological state, the findings of these experiments were so clear that changes in the experimental method would be unlikely to change the main conclusions. The simulated trochlear dysplasia reduced lateral stability of the patella significantly compared with normal knees. Trochleoplasty increased stability, to a level not significantly different from that of the normal knee. This objective biomechanical evidence supports the place of trochleoplasty in the treatment of severe trochlear dysplasia and symptomatic instability.

This work was supported partly by a project grant from the Arthritis Research Campaign, plus an equipment grant for the Instron machine. The Flock of Birds was provided by an equipment grant from the Royal Society of London. We also thank the Pathology Department and Patient Affairs Office of Ealing Hospital, the source of our specimens.

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


4. Henry JH, Goletz TH, Williamson B. Lateral retinacular release in patellofemoral subluxation: indications, results, and comparison to open patellofemoral reconstruc-