Single bundle anterior cruciate reconstruction does not restore normal knee kinematics at six months

AN UPRIGHT MRI STUDY

Abnormal knee kinematics following reconstruction of the anterior cruciate ligament may exist despite an apparent resolution of tibial laxity and functional benefit. We performed upright, weight-bearing MR scans of both knees in the sagittal plane at different angles of flexion to determine the kinematics of the knee following unilateral reconstruction (n = 12). The uninjured knee acted as a control. Scans were performed pre-operatively and at three and six months post-operatively. Anteroposterior tibial laxity was determined using an arthrometer and patient function by validated questionnaires before and after reconstruction. In all the knees with deficient anterior cruciate ligaments, the tibial plateau was displaced anteriorly and internally rotated relative to the femur when compared with the control contralateral knee, particularly in extension and early flexion (mean lateral compartment displacement: extension 7.9 mm (SD 4.8), p = 0.002 and 30° flexion 5.1 mm (SD 3.6), p = 0.004). In all ten patients underwent post-operative scans. Reconstruction reduced the subluxation of the lateral tibial plateau at three months, with resolution of anterior displacement in early flexion, but not in extension (p = 0.015). At six months, the reconstructed knee again showed anterior subluxation in both the lateral (mean: extension 4.2 mm (SD 4.2), p = 0.021 and 30° flexion 3.2 mm (SD 3.3), p = 0.024) and medial compartments (extension, p = 0.049).

Our results show that despite improvement in laxity and functional benefit, abnormal knee kinematics remain at six months and actually deteriorate from three to six months following reconstruction of the anterior cruciate ligament.

The anterior cruciate ligament (ACL) is a complex structure designed to perform many refined roles. Following its disruption, surgical reconstruction aims to eliminate symptomatic instability and restore the normal kinematics, in order to prevent further injury and risk of degenerative change in the future.1 Despite functional benefits and reduction of anteroposterior laxity following successful ACL reconstruction, abnormal kinematics of the knee persist.2,3 Gait analysis has shown that ACL deficient knees have anterior tibial translation with excessive internal rotation of the tibia in relation to the femur at early angles of flexion,4 which persist after reconstruction.5-7 These findings have also been confirmed in radiological studies despite restoration of passive laxity and improved function.3,8

MR imaging of the knee allows precise identification of the articulating surfaces. The use of the Flexion Facet Centre technique9 allows detection of kinematic changes in an upright weight-bearing model that replicates normal weight bearing, which we have previously demonstrated to be a valid and repeatable technique.10 Logan et al2 demonstrated that anterior tibial subluxation in the lateral compartment was present following ACL reconstruction using the Flexion Facet Centre technique in weight-bearing scans, but they did not record pre-operative measurements for comparison. Moreover, currently there are no prospective studies which have looked at the kinematics of the knee following ACL reconstruction using upright weight-bearing MRI.

We have therefore undertaken a prospective study to investigate the tibiofemoral relations of ACL deficient patients before and after reconstruction of the ACL using an upright, weight-bearing MR scan and the Flexion Facet Centre technique. Our hypothesis was that in an upright weight-bearing setting, ACL reconstruction does not reduce the kinematic abnormalities found in the ACL deficient knee.

Patients and Methods
Between December 2008 and May 2009, 12 patients with a confirmed unilateral ACL rupture, who were awaiting reconstructive surgery, were invited to participate in our study.
Patients were excluded if they had multiple ligament injuries, bilateral ACL injury, significant pre-existing pathology of the ankles, knees or hips, were unable to undergo an MR scan or give consent. Patients with injury to the menisci were included. Patients were given an information sheet and the opportunity to discuss the project, prior to providing informed consent to participate in accordance with the approval granted by the Local Research Ethics Committee. Our previous work suggested that a cohort of 12 patients would be a suitable sample size,\textsuperscript{10} although a formal power calculation was not performed. The mean age of the patients was 30 years (16 to 43), and there were three women and nine men. The mean time from injury to surgery was 32 months (2 to 132). The injuries were sustained during football in eight patients, and rugby, trampolining, horse riding and a fall in one patient each. All had symptomatic instability.

All patients underwent an arthroscopic-assisted ACL reconstruction using a transtibial technique with a four-strand hamstring autograft (gracilis and semitendinosus), utilising endobutton fixation on the femoral side and a RCI screw on the tibial side (Smith & Nephew Ltd, Memphis, Tennessee). The senior author (AGS) performed all the operations and all the patients followed a standardised accelerated rehabilitation programme.

MR scans were performed using the Upright, Positional MRI scanner (FONAR Corp., Melville, New York) (Fig. 1). Patients were positioned standing on the positional MRI deck at a reclined angle of 30°, thus adopting a stable, representative weight-bearing stance; feet were placed shoulder width apart and facing forward. A 45° abdominal-torso coil around the knees allowed simultaneous imaging of both knees. T2 weighted sagittal images were obtained (TR = 1638 ms, TE = 132 ms) after an initial ‘scouting’ transverse image scan (Fig. 2). Three sagittal slices, each 4.5 mm apart, were then obtained to allow modelling of the centre of the condyle. Scans were performed with the knees at full extension and at flexion angles of 30°, 60° and 90°, measured on both knees with a goniometer, referencing the midpoint of the joint margin in the sagittal plane.

The Osiris software (University Hospital of Geneva, Geneva, Switzerland) was used to analyse images to within 0.1 mm. The flexion facet centre of each condyle was identified (Fig. 3).\textsuperscript{9,10} The relative position of the posterior tibia and the flexion facet centre could then be measured in the medial and the lateral compartments. It is well known that in a given individual, the right and left knee show near-identical kinematics.\textsuperscript{10-12} The healthy contralateral knee in each patient therefore acted as a control. All the measurements were performed by the primary researcher (JAN) using a validated and reliable technique.\textsuperscript{10}

At each follow-up point, anteroposterior laxity was assessed using the KT-1000 Arthrometer (Medmetric, San Diego, California) and patients completed the following validated questionnaires: Anterior Cruciate Ligament Quality of Life questionnaire (ACLQoL);\textsuperscript{13} Tegner sports activity questionnaire;\textsuperscript{14} Short Form-12 (SF-12) physical component summary (PCS) and mental component summary (MCS).\textsuperscript{15}

**Statistical analysis.** Statistical analysis was carried out using SPSS v.17 (SPSS Inc., Chicago, Illinois). The respective positions (mean and standard deviation (SD)) of the femur and tibia were compared with the contralateral side at various angles of flexion. For statistical comparison the Wilcoxon signed rank test was used, as data were not normally distributed. The level of statistical significance for all tests was set at a p-value < 0.05.
Table I: Comparison of the mean (SD) movement of the flexion facet centre (FFC) in anterior cruciate ligament (ACL) deficient and normal control knees at various knee flexion angles (M, medial; L, lateral)

<table>
<thead>
<tr>
<th>Posterior tibial cortex to FFC (mm)</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>ACL deficient</td>
<td>20.8 (3.8)</td>
<td>19.4 (6.7)</td>
<td>26.9 (4.9)</td>
<td>18.9 (6.1)</td>
</tr>
<tr>
<td>Control</td>
<td>22.6 (3.4)</td>
<td>25.9 (5.0)</td>
<td>28.7 (4.8)</td>
<td>23.3 (5.2)</td>
</tr>
<tr>
<td>Mean difference</td>
<td>2.6 (3.1)</td>
<td>7.9 (4.8)</td>
<td>2.1 (4.5)</td>
<td>5.1 (3.6)</td>
</tr>
<tr>
<td>p-value</td>
<td>0.056</td>
<td>0.002</td>
<td>0.195</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Fig. 3
Sagittal MRI scan showing flexion facet centre (FFC). The measurement of ‘d’ is taken from the posterior tibial cortex parallel with the tibial plateau.

Results
The mean pre-operative side-to-side difference on the KT-1000 arthrometer was 7.7 mm (5 to 10). Questionnaires revealed significant functional impairment: ACLQoL mean score of 40.7 (16.3 to 82.5), Tegner sports mean score of -3.6 (-9.0 to -1.0) and SF-12 PCS mean score of 46.8 (34.8 to 56.2) and mean MCS score of 51.1 (23.4 to 63.9). In seven patients meniscal tears were present (two medial, three lateral, and two with tears of both). Passive laxity and questionnaire findings were comparable to those in patients with intact menisci.

In the healthy control knee the medial tibial plateau sat centrally in extension, moved posteriorly in early flexion, stabilised in mid-flexion and finally moved slightly forwards at 90° degrees of flexion. During flexion, the lateral tibia moves progressively anteriorly during the arc of flexion and so, the tibia rotates internally relative to the femur during flexion; or externally from flexion to extension, the so-called screw-home mechanism (Table I). In the ACL deficient knee, the medial tibia was anteriorly displaced in extension, moved posteriorly in early flexion and then stabilised (Table I, Fig. 4). The lateral tibia was significantly anteriorly displaced in extension and early flexion (mean lateral compartment displacement: extension 7.9 mm (SD 4.8), p = 0.002 and 30° flexion 5.1 mm (SD 3.6), p = 0.004), and only resolved to that of the control knee at 90°, constituting excessive internal rotation of the tibia in early flexion.

A total of ten patients completed three- and six-month scans; the two patients that were unable to attend scan appointments were unexpectedly out of the country. Of those with meniscal tears (n = 7), three required trimming of the lateral meniscus during the ACL reconstruction. Passive laxity was restored to within normal limits in all patients (mean side-to-side difference 0.5 mm (-2 to 2)); Lachman’s and pivot shift tests also showed no sign of ACL

Fig. 4
Line graph showing the mean anterior displacement of the medial and lateral tibial plateau of the anterior cruciate ligament injured knee in comparison with the control knee.

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deficiency. Improvements were noted in the mean ACLQoL score to 60.5 (49.0 to 69.7), the mean Tegner score to -1.4 (-2 to 0) and the mean SF-12 score in both categories: PCS 49.2 (42.3 to 56.8) and MCS 54.2 (46.2 to 59.5).

The medial tibial plateau of the reconstructed knee followed a similar pattern to that of the control knee, and the initial anterior displacement seen in the ACL deficient knee had been reduced (Table II, Figs 5 and 6). The lateral tibial plateau subluxed anteriorly in extension (mean lateral compartment displacement 4.4 mm (SD 4.4), p = 0.015), resolving by 30° of flexion (mean lateral compartment displacement 0.9 mm (SD 3.9), p = 0.374) and thereafter demonstrating normal progressive anterior shift through flexion.

At six months, ten patients underwent MRI scans. Passive laxity was maintained at a mean side-to-side difference of 0.5 mm (-2 to 2) along with a stable Lachman and pivot shift test.

The mean ACLQoL continued to improve at 67.9 (SD 12.6, 47.4 to 86.4), the mean Tegner sports score was comparable with the score at three months (-1.8 (SD 1.2, -4 to 0)), and the mean SF-12 continued to improve for the physical component PCS at 53.3 (SD 6.7, 38.1 to 62.0) with slight decrease in the MCS at 52.2 (SD 11.9, 21.7 to 58.9).

On the MR scans, the medial tibial plateau showed a similar pattern of movement to the control knee, with slight anterior translation at 60° of flexion (Table III, Fig. 7). The lateral tibial plateau remained anteriorly displaced in extension as at three months (mean lateral compartment displacement 4.2 mm (SD 4.2), p = 0.021), but this did not resolve at 30° as it had at three months (mean lateral compartment displacement 3.2 mm (SD 3.3), p = 0.024).

In those patients with meniscal tears, tibiofemoral readings were comparable with those of patients with intact menisci. No significant differences or discernible trends were ascertained for either compartment throughout the arc of flexion at each stage of follow-up. When, control knees were compared with the pre-operative observations no significant changes were observed for either compartment.

Discussion
This is the first study that has used the upright weight-bearing MRI scans to study tibiofemoral kinematics in a prospective cohort before and after an ACL reconstruction. Our results indicate that the control knees demonstrate internal rotation of the tibia in relation to femur primarily due to anterior movement of the lateral tibia during flexion, which is consistent with previous studies. The tibia was internally rotated in extension and early flexion, with more anterior displacement laterally than medially. Our findings are similar to other studies using the upright MRI scanner and other radiological studies, and offer the advantage over gait studies of measuring true joint relations, rather than relying on skin-based marker systems. Supine scanning found relatively minor changes in tibiofemoral contact points in ACL deficient patients, but these data do not appear to represent true weight-bearing, even when a leg press is added; a radiological study found a substantial increase in anterior tibial translation in ACL deficient knees when converting from non-weight-bearing to weight-bearing. The noted internal rotation is thought to be a product of the shape of the tibial plateau and restriction of the posterior horn of the medial meniscus. Patients with meniscal tears were included in our study due to the high prevalence found in the ACL injured population and the difficulties in accurately identifying such injuries prior to recruitment. Given the small number of meniscal tears present in our cohort, their impact on kinematic function could not be fully ascertained. The temporality of meniscal tears and joint stability remains ambiguous in the ACL.

Table II. Comparison of the mean (SD) movement of the flexion facet centre (FFC) in anterior cruciate ligament (ACL) reconstructed and normal control knees at various knee flexion angles at three months (M, medial; L, lateral)

<table>
<thead>
<tr>
<th>Angle of knee flexion (º)</th>
<th>Posterior tibial cortex to FFC (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
</tr>
<tr>
<td>0º</td>
<td>21.9 (4.0)</td>
</tr>
<tr>
<td>30º</td>
<td>22.7 (4.0)</td>
</tr>
<tr>
<td>60º</td>
<td>0.9 (1.8)</td>
</tr>
<tr>
<td>90º</td>
<td>0.163</td>
</tr>
</tbody>
</table>

Fig. 5
Line graph showing the anterior displacement of the medial and lateral tibial plateau of the anterior cruciate ligament reconstructed knee at three months in comparison with the control knee.
deficient knee. The contribution of meniscal tears to kinematics is complex, but does appear to impact on their function as secondary stabilisers.

Post-operative scans of the reconstructed knees were performed at three and six months. Restoration of normal passive tibial laxity was achieved (KT-1000 mean side-to-side difference of 0.5 mm) along with a stable Lachman and pivot shift test at three and six months. Patient derived function was improved post-operatively as assessed by the Tegner sports activity score and both components of the SF-12 health survey. The mean ACLQoL questionnaire pre-operatively was 40.7, and this increased to a mean of 60.5 at three months and 67.9 at six months, although this is still below the mean value (> 90) found in the absence of an ACL injury.

At three months, the ACL reconstructed knee had a reduction of the abnormal internal rotation in early flexion, although the lateral plateau remained anteriorly displaced in extension, albeit improved in comparison with the ACL deficient knee (4.4 mm vs 7.9 mm, respectively). However, at the six-month follow-up stage kinematic findings had deteriorated towards the pre-operative findings. The medial tibial plateau showed an increased anterior displacement in extension. The lateral plateau showed anterior displacement from extension to 60° of flexion, producing excessive internal rotation of the tibia in early flexion, although not to the extent found pre-operatively.

A reconstruction that restores the anterior tibial laxity to within 3 mm of the healthy contralateral knee is generally considered successful, although this is not always achieved. All of our patients had restoration of normal anteroposterior laxity and significant improvement in their functional scores. In spite of these positive findings, kinematic abnormalities remain, and in fact deteriorated between three and six months following surgery. The ACL graft undergoes a dynamic process of maturation and adaptation in the months following implantation. In animal studies mechanical changes in strength, elongation and stiffness have been observed in the first 12 weeks, and by 12 months revascularisation and collagen fibre organisation have produced a graft similar to that of the native ACL. However, passive laxity does not appear to increase during this period. Strain in the ACL is dramatically increased from the transition to weight-bearing and is the greatest in extension and early flexion. The re-emergence of subluxation of the lateral tibial plateau in early flexion could demonstrate the reduced ability of the new graft to resist anterior displacement of the tibia over time.

Immediate movement and weight-bearing in early rehabilitation have been shown to have positive effects on

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**Table III.** Comparison of the mean (SD) movement of the flexion facet centre (FFC) in anterior cruciate ligament (ACL) reconstructed and normal control knees at various knee flexion angles at six months (M, medial; L, lateral)

<table>
<thead>
<tr>
<th>Posterior tibial cortex to FFC (mm)</th>
<th>0° M</th>
<th>0° L</th>
<th>30° M</th>
<th>30° L</th>
<th>60° M</th>
<th>60° L</th>
<th>90° M</th>
<th>90° L</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL reconstructed</td>
<td>20.6 (4.8)</td>
<td>21.2 (3.5)</td>
<td>25.5 (3.8)</td>
<td>18.6 (6.0)</td>
<td>18.6 (3.6)</td>
<td>18.0 (4.5)</td>
<td>21.6 (2.9)</td>
<td>16.5 (3.9)</td>
</tr>
<tr>
<td>Control</td>
<td>22.1 (3.8)</td>
<td>25.3 (3.9)</td>
<td>26.8 (4.3)</td>
<td>21.8 (4.6)</td>
<td>28.1 (4.0)</td>
<td>20.6 (3.7)</td>
<td>25.3 (3.2)</td>
<td>17.0 (4.2)</td>
</tr>
<tr>
<td>Mean difference</td>
<td>1.5 (2.1)</td>
<td>4.2 (4.2)</td>
<td>1.3 (2.7)</td>
<td>3.2 (3.3)</td>
<td>1.6 (2.1)</td>
<td>2.6 (4.3)</td>
<td>-0.4 (2.1)</td>
<td>0.5 (4.4)</td>
</tr>
<tr>
<td>p-value</td>
<td>0.049</td>
<td>0.021</td>
<td>0.169</td>
<td>0.024</td>
<td>0.062</td>
<td>0.096</td>
<td>0.677</td>
<td>0.623</td>
</tr>
</tbody>
</table>

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MRI sagittal images of flexion facet centre measurements of lateral condyle at 30° of flexion in one participant, in a) a control knee (30.7 mm), b) an anterior cruciate ligament deficient knee (21.2 mm), and c) an anterior cruciate ligament reconstructed knee at three months (27.1 mm).
the clinical and the functional outcome but it is uncertain how rapid should this be. Studies comparing accelerated with non-accelerated programmes have shown few differences in laxity, functional outcome and patient satisfaction at follow-up, although concern remains that too-rapid rehabilitation will stretch the graft. Concern has also been raised about the effect on dynamic tibial stabilisation of the hamstring harvest, although our findings demonstrate excessive movement of the lateral tibial plateau after harvesting the medial hamstring tendons.

Chronic ACL deficiency is associated with degenerative osteoarthritis, particularly in the medial compartment. It has also been suggested that persistent kinematic abnormalities create an abnormal loading environment and risk further meniscal injury. The ability of ACL reconstruction to prevent osteoarthritis remains controversial, but may be important and certainly protects the menisci from further injury.

The double bundle ACL reconstruction has been proposed as a more anatomical surgical option, with improved kinematics. Evidence for its efficacy is yet to be shown in terms of subjective benefit, restoration of tibial laxity or kinematic findings, although some studies have shown improved pivot shift results. The use of the upright MRI scanner may allow an early assessment of the potential kinematic benefits of such an approach.

The main strengths of this study are that the patients were followed-up longitudinally before and after ACL reconstruction by a single surgeon, using a reliable technique. There were a few limitations of our study. Compromises were made in imaging in the upright position to reduce imaging time (only essential sagittal images across each condyle were captured, guided by transverse scout images). Although there is the possibility of variability in the positioning of sagittal sections, our results in the control knees were remarkably consistent, demonstrating the strength of the techniques used. Improvements in scanning speed in open scanning environments may eventually allow sagittal and coronal scan acquisition and three-dimensional modelling of kinematics, but this was not possible without excessive imaging times for our patients.

There is certainly scope for further work in this area. A larger cohort could be recruited to study the effect of meniscal injury on kinematics of the knee. Later imaging will also allow monitoring of the progression of maturation of the graft and musculoskeletal changes. Additionally, the kinematic implications of different graft materials, rehabilitation strategies and extra-articular knee supports would all be of interest in light of our findings.

In conclusion, ACL reconstruction reduces anterior subluxation and rotation of the tibia creating a more normal pattern of movement during active weight-bearing, as assessed by an upright MRI scan. To the best of our knowledge this is the first study showing that the in vivo weight-bearing kinematics of the knee deteriorate from three to six months following reconstruction. This may reflect adaptation of the graft and/or muscle imbalances during rehabilitation. If abnormal joint relations persist, they are likely to contribute to the development of osteoarthritis often seen after ACL injury and also reconstruction.

**Supplementary material**

A further opinion by Mr C. Gupte is available with the electronic version of this article on our website at www.bjs.org.uk/education/further-opinions

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**


