

# Intraoperative measurement of knee kinematics in reconstruction of the anterior cruciate ligament

A. M. J. Bull, P. H. Earnshaw, A. Smith, M. V. Katchburian,  
A. N. A. Hassan, A. A. Amis

*From Imperial College, and Guy's and St Thomas' Hospital NHS Trust, London, England*

**O**ur objectives were to establish the envelope of passive movement and to demonstrate the kinematic behaviour of the knee during standard clinical tests before and after reconstruction of the anterior cruciate ligament (ACL). An electromagnetic device was used to measure movement of the joint during surgery.

Reconstruction of the ACL significantly reduced the overall envelope of tibial rotation (10° to 90° flexion), moved this envelope into external rotation from 0° to 20° flexion, and reduced the anterior position of the tibial plateau (5° to 30° flexion) ( $p < 0.05$  for all). During the pivot-shift test in early flexion there was progressive anterior tibial subluxation with internal rotation. These subluxations reversed suddenly around a mean position of  $36 \pm 9^\circ$  of flexion of the knee and consisted of an external tibial rotation of  $13 \pm 8^\circ$  combined with a posterior tibial translation of  $12 \pm 8$  mm. This abnormal movement was abolished after reconstruction of the ACL.

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Reconstruction of a ruptured anterior cruciate ligament (ACL) seeks to prevent episodes of instability, to give the patient confidence in the knee and to reduce pain. It has been successful in restoring normal anteroposterior tibio-femoral stability to the injured knee.<sup>1</sup> The relationship,

however, between details of the surgical procedure and the long-term consequences of such surgery are not known. The correlation between the clinical results and the development of osteoarthritis is not clear and some authors have even suggested that there may be a greater tendency to develop arthritis in ACL-deficient knees which have undergone reconstruction, compared with those which have not.<sup>2,3</sup> A number of hypotheses have been postulated to explain this observation. One implicates the failure to re-establish normal joint kinematics in regard to the ligament itself (isometry, tensioning, fixation, graft length) or the heterogeneity of the soft-tissue injury.

Our aim therefore was to assess the alteration of kinematics of the knee during reconstruction of the ACL. A specific objective was to establish the envelope of passive movement, which is the range of internal and external rotation of the tibia which the knee may exhibit across the range of flexion.<sup>4</sup> We also wished to demonstrate the kinematics of the knee during standard clinical laxity tests, including the pivot shift, and the effect of reconstruction of the ACL on these.

## Patients and Methods

An electromagnetic device, the 'flock of birds' (Ascension Technology, Burlington, Vermont), was used to measure movement of the joint. This has an accuracy of 0.23% of the step size for translations and 1.8% of the step size for rotations when used within an optimal operational zone, for which the transmitter-to-receiver separation is between 271 and 723 mm.<sup>5</sup> The configuration consisted of a transmitter which produced the electromagnetic field, and three receivers, one each for the tibia and femur and one to digitise anatomical landmarks so that a standardised co-ordinate system could be used to define the movements.<sup>6</sup> The operating theatre was set up so that the electromagnetic device was within its optimal operational zone and there was no interference from ferromagnetic materials.<sup>7</sup> This has been used previously to quantify kinematics in the ACL-deficient knee in vitro.<sup>8</sup>

The study group consisted of ten patients undergoing reconstruction for isolated injury to the ACL. Their mean age was 30.8 years (19 to 40) and there were eight men and two women, seven right knees and three left knees. The

A. M. J. Bull, PhD, ARC Lecturer

Bagrit Centre, Department of Bioengineering, Imperial College of Science, Technology and Medicine, London SW7 2BX, UK.

P. H. Earnshaw, FRCS C, Consultant Orthopaedic Surgeon

A. Smith, FRCS Ed, Orthopaedic Registrar

A. N. A. Hassan, FRCS Orth, Apley Research Fellow

Guy's and St Thomas' Hospital NHS Trust, London SE1 9RT, UK.

M. V. Katchburian, FRCS Orth, Clinical Fellow in Paediatric Orthopaedics  
Hôpital de la Timone, Service de Chirurgie Infantile et Orthopédie, 264 Rue Saint-Pierre, 13385 Marseille, France.

A. A. Amis, DSc, Professor of Orthopaedic Biomechanics

Departments of Mechanical Engineering and Musculoskeletal Surgery, Imperial College of Science, Technology and Medicine, London SW7 2BX, UK.

Correspondence should be sent to Dr A. M. J. Bull.

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International Knee Documentation Committee 1995 grading was C (abnormal) for five patients and D (severely abnormal) for the remainder. Approval was granted by the Guy's & St Thomas' Hospital Ethics Committee, and informed consent was given by each patient for the investigation to be made. A mid-third bone-patellar tendon-bone graft was used for the reconstruction. The procedure was carried out via a small arthrotomy through the retropatellar fat pad.

After harvesting the graft and preparing the bone tunnels, the electromagnetic tracking receivers were fixed to the tibia and femur using sterile mounting blocks. Each block was fixed to the bone using two 2.0 mm diameter threaded Kirschner (K-) wires. These were placed so that they did not transfix moving ligaments or other subcutaneous structures (Fig. 1). This fixation method had been tested in the laboratory on whole cadaver limbs before use in vivo, to check that the electromagnetic tracking receivers did not move relative to the underlying bones during manipulations. In addition, during surgery, the mounting blocks were kept in view so that if they were knocked it was assumed that they might have moved and the experiment was then abandoned. The electromagnetic receivers and cables were contained in sterile plastic sleeves before insertion in the mounting blocks. The anatomical landmarks which were digitised using the third receiver with an attached stylus, were the proximal tibia (on the anterior tibial spine below the tibial tubercle), the distal tibia (on the anterior tibia approximately 50 mm distal to the first point), the medial tibial plateau (just below the joint line on the most medial point of the tibia), the lateral tibial plateau (just below the joint line on the most lateral point of the tibia) and the medial and lateral femoral condyles. The position of the centre of the hip was calculated by moving the leg about the hip and calculating the centre of rotation of this movement. Knowledge of the positions of these points in relation to the electromagnetic receivers attached to each bone allowed bone-to-bone movement to be described in clinical terms.

Clinical movements were passively carried out and measured for the ACL-deficient knee. The movements were: the anterior drawer (with the knee flexed to 90°), the Lachman test (at 20° to 30° of knee flexion), the pivot shift and knee flexion/extension while holding the foot and applying torques to induce internal, external, or neutral tibial rotation. These clinical tests yielded the kinematic data to define the envelope of passive movement and were graded subjectively by the surgeon. In order to avoid prolongation of the time under anaesthesia, the surgeon applied forces and moments by hand, rather than using instrumented systems for each load. The graft was tensed manually at 90° of knee flexion and the bone blocks were fixed by interference screws; the clinical movements were then repeated. All patients achieved full extension of the knee. The mean time added to the procedure in order to make these measurements was  $12.4 \pm 2.5$  minutes. Full

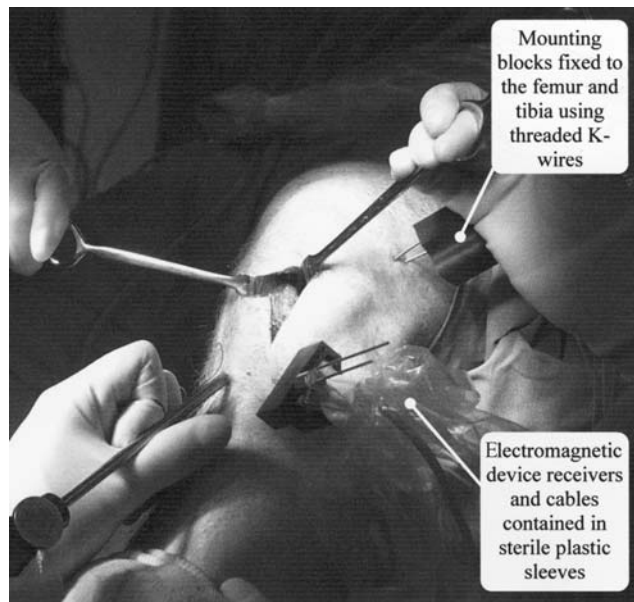


Fig. 1

Photograph showing the intraoperative arrangement with the movement sensors fixed to the tibia and femur.

'six-degree-of-freedom' kinematics were computed and described in terms of flexion, rotation, abduction, anterior translation, distraction, and lateral shift. These describe the position of the tibia relative to the femur, according to a three-cylinder open-chain mechanism.<sup>6</sup>

The tibial translations and coupled rotations during the drawer test were compared before and after fixation of the graft using a paired, one-tail *t*-test as were kinematic data at 5° intervals before and after graft fixation. Significance was set at the 5% level.

The clinical assessment of translation during the Lachman and anterior drawer tests and during the pivot-shift reduction (the 'shift'), was described as 0 to 3+. This was scaled from 0 to 3.5 in increments of 0.5; for example, a clinical assessment of 2+ was scaled as 2.5. These non-parametric grades were tested for correlation with the translations obtained from the kinematic data using correlation analysis which returns the covariance of the two data sets divided by the product of their standard deviations. Correlation analysis was used to compare the tibial rotation during the reduction component of the pivot shift, with the tibial rotation envelope obtained at the flexion angle at which the pivot-shift reduction occurred.

## Results

**Drawer test.** The anterior tibial translations relative to the femur during the drawer test are presented in Table I. Reconstruction reduced the anterior drawer and Lachman drawer translation by 55% ( $p < 0.00001$ ) and 72% ( $p < 0.00001$ ), respectively. On average, both the Lachman and anterior drawer tests induced a coupled internal tibial rotation, both before and after reconstruction of the ACL. The standard deviations about the means (Table I) show, how-

**Table I.** Mean ( $\pm$  SD) anterior tibial translation and coupled internal tibial rotation during the drawer test

	Lachman test		Anterior drawer test	
	Anterior translation (mm)	Coupled internal tibial rotation (degrees)	Anterior translation (mm)	Coupled internal tibial rotation (degrees)
Before reconstruction	16.0 $\pm$ 4.0	3.8 $\pm$ 3.3	13.2 $\pm$ 3.5	3.4 $\pm$ 3.5
After reconstruction	4.5 $\pm$ 1.3	1.0 $\pm$ 1.1	5.9 $\pm$ 2.0	2.2 $\pm$ 2.0
Reduction	11.5 $\pm$ 4.6*	2.8*	7.3 $\pm$ 3.8*	1.3

\*p < 0.00001

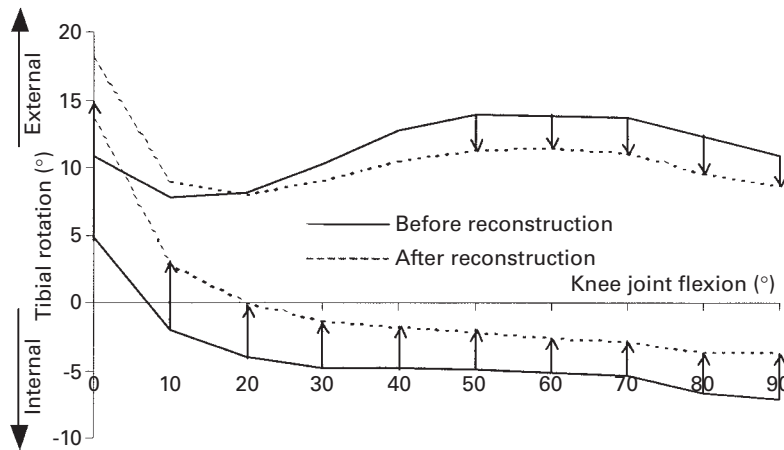


Fig. 2

Graph showing the mean envelope of tibial rotation with manual application of torque at the foot.

ever, that some knees had an external tibial rotation demonstrable during clinical testing. The kinematic data were used to quantify the knee flexion angles at which the drawer test was conducted. The anterior drawer test was conducted at  $75 \pm 12^\circ$  of flexion, and the Lachman test at  $22 \pm 9^\circ$ .

**Envelope of movement.** The values obtained for passive movement with the heel cupped in the hand to maintain neutral tibial rotation, were not consistent within subjects. These data are not presented. The mean envelope of movement, showing the tibial rotation during knee flexion with an induced tibial rotation torque, is presented in Figure 2. The arrows show significant differences. Tibial internal rotation was significantly reduced from  $0^\circ$  to  $90^\circ$  ( $p < 0.05$ ), as was tibial external rotation from  $50^\circ$  to  $90^\circ$  ( $p < 0.05$ ). The overall tibial rotation envelope was reduced from  $10^\circ$  to  $90^\circ$  ( $p < 0.05$ ). Figure 2 also shows that reconstruction of the ACL moved the envelope of tibial rotation into external rotation near extension ( $0^\circ$  to  $20^\circ$  of flexion), and had no overall effect on the mean position of tibial rotation at greater angles of knee flexion. The position of the tibial plateau during flexion/extension with the tibia in various positions of rotation showed significantly less anterior subluxation with the graft secured. This corresponded to a reduction of 4.5 mm in the anteriorly subluxed position of the tibia, during knee flexion with internal tibial rotation from  $10^\circ$  to  $25^\circ$  of flexion ( $p < 0.05$ ), and a reduc-

tion of 4.7 mm with external tibial rotation at  $5^\circ$ ,  $15^\circ$ ,  $20^\circ$ , and  $30^\circ$  of flexion of the knee ( $p < 0.05$ ). Thus, the injured knees flexed and extended in an anteriorly subluxed position near extension, which was reduced after reconstruction.

**Pivot-shift test.** The pivot shift was positive in all patients before reconstruction of the ACL. After surgery this reversed to negative on clinical testing (Figs 3 and 4). Between  $0^\circ$  and  $25^\circ$  of flexion, the ACL-deficient knee showed progressive tibial subluxation anteriorly and internal rotation from a position of neutral tibial rotation (Fig. 5). These subluxation changes reversed suddenly with the displacement of the 'pivot shift', at a mean flexion angle of  $27^\circ$ . The reduction component of the pivot-shift tests (the 'shift') occurred around a mean position of  $36 \pm 9^\circ$  of flexion of the knee over a range of  $18 \pm 9^\circ$  of flexion, and was an external tibial rotation of  $13 \pm 8^\circ$  with a combined posterior tibial translation of 12 mm ( $\pm 8$  mm). These values are explained in Figure 5, a typical pivot shift from one subject.

The pivot-shift region was defined by the posterior translation of the tibia because this was a more clearly defined event than the changes in rotation. The pivot shift can be demonstrated as a rotation and translation of the tibial plateau when viewed in the transverse plane. Figure 6 presents the pivot-shift test in terms of movement of a normalised tibial plateau. The movements during an attempt

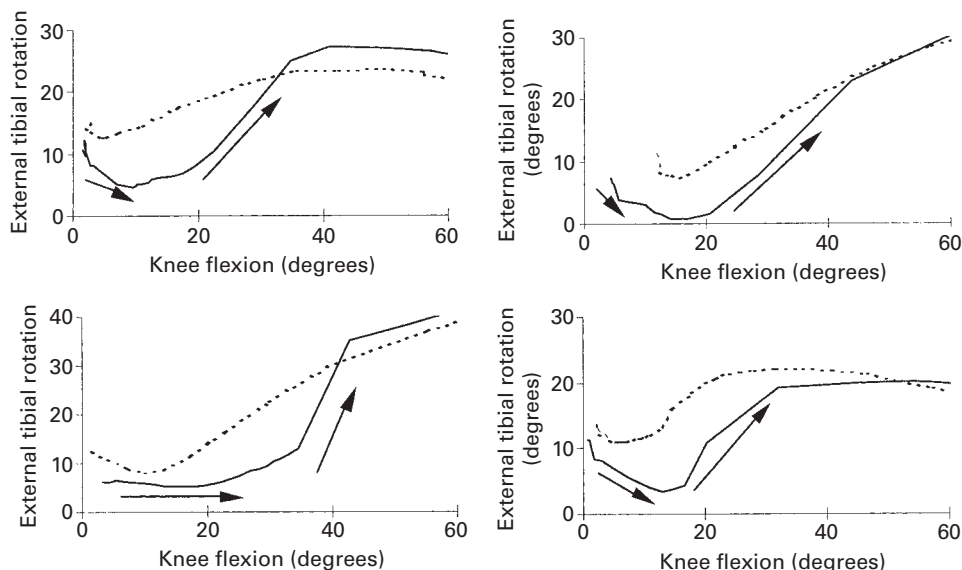


Fig. 3

Graphs showing the effect of reconstruction on the tibial rotation characteristics during the pivot-shift test in four knees. Subluxations followed by reductions as the knees flex are indicated by the arrows.

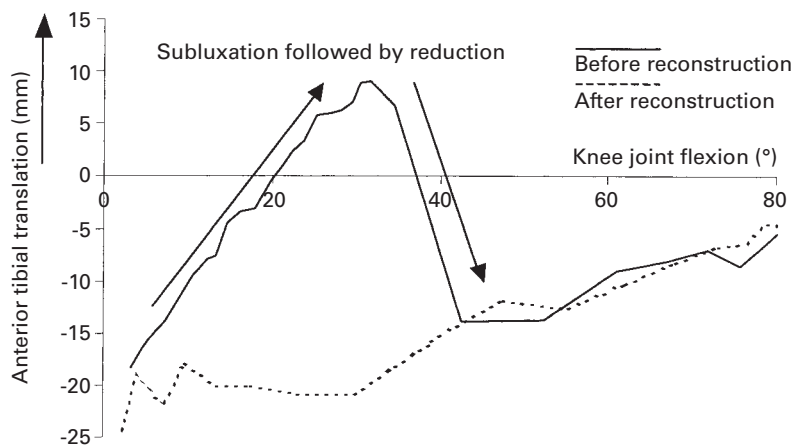


Fig. 4

Graph showing the effect of reconstruction on the anterior translation characteristics of the centre of the tibia during the pivot-shift test.

to elicit the pivot shift, after reconstruction of the ACL, are also presented for the same ranges of flexion over which the pivot shift had been elicited. Figure 6 shows that the behaviour of the knees was variable before reconstruction. The mediolateral lines show clearly the relative contributions of translation and rotation, and indicate an approximate centre about which the movements occurred. In all ten knees these translations and rotations occurred about an axis medial to the centre of the knee before reconstruction. At one extreme, the tibia of one subject (case 7) rotated about an almost central point, with very little translation. Conversely, another patient (case 4) had a posterior translation of the tibia, but almost no rotation as the joint suddenly reduced. By contrast, behaviour was more consistent after reconstruction, with translations and rotations occurring about an axis lateral to the centre of the knee in seven of nine cases. Three of those knees were left-sided: their tracings have been reversed in Figure 6 for ease of comparison.

**Correlation with clinical assessment.** The translations measured using the kinematic data were positively correlated with the clinical grade for the anterior drawer test ( $R = 0.716$ ). There was a weak correlation between the translations measured and the clinical grade for the pivot-shift test ( $R = 0.446$ ), but no correlation between the translations measured and the clinical grade for the Lachman test ( $R = 0.122$ ). There was a weak correlation between the tibial rotation during the reduction component of the pivot shift and the tibial rotation envelope obtained at the flexion angle at which the pivot-shift reduction occurred ( $R = 0.498$ ).

## Discussion

We believe that this is the first time that the effect of reconstruction of the ACL on six-degree-of-freedom kinematics of the knee has been documented in vivo. The intra-operative measurements showed that reconstruction of the

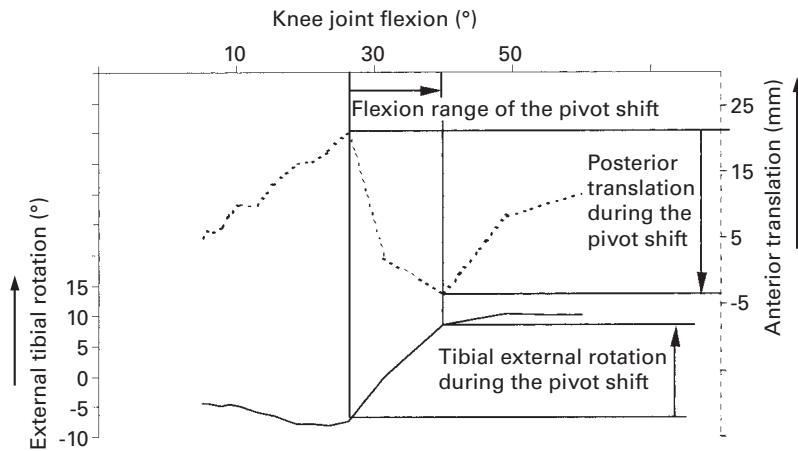


Fig. 5

Graph showing a typical pivot shift with simultaneous posterior translation and external rotation of the tibia when the pathological subluxation suddenly reduced.

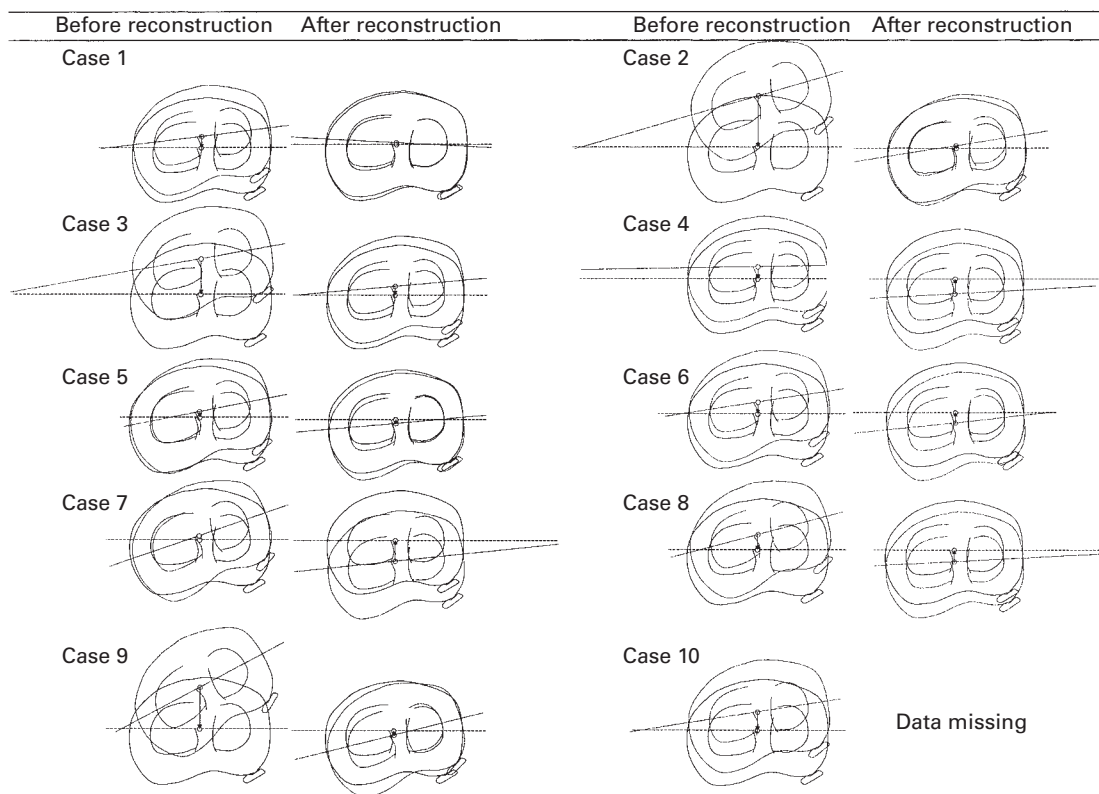


Fig. 6

Diagram showing movement of the tibial plateau during the pivot-shift test before and after reconstruction over the same range of flexion (tracings transposed to appear to be the right side).

ACL provided significant reduction in anterior tibial translation during the drawer test. It has been found that a consistently applied anterior drawer test with a central axis of rotation produced a tibial internal rotation.<sup>9</sup> Fixing the axis of rotation has only been achievable in vitro. Application of tests by hand is variable, and the forces and moments are not precisely reproducible. This leads to variable kinematics. Table I shows only small and inconsistent rotational effects. Therefore, tibial rotation during the drawer test is not relevant to the diagnosis of rupture of the ACL even although this is important in the assessment of peripheral damage.

We were surprised not to find a better correlation between the subjective grading of anterior drawer and Lachman tests and the measured anterior translations. This provides further evidence of the need to use instrumented assessment, such as the KT1000 (MEDmetric Corporation, Sand Diego, California) or the Rolimeter (Aircast Europa GmbH, Neubeuern, Germany) in order to make precise measurements during surgery. One reason for the disparity between the measured translation and the clinical grade could be that the clinical subjective grade is also affected by the sensitivity of the examiner's hand in respect of soft

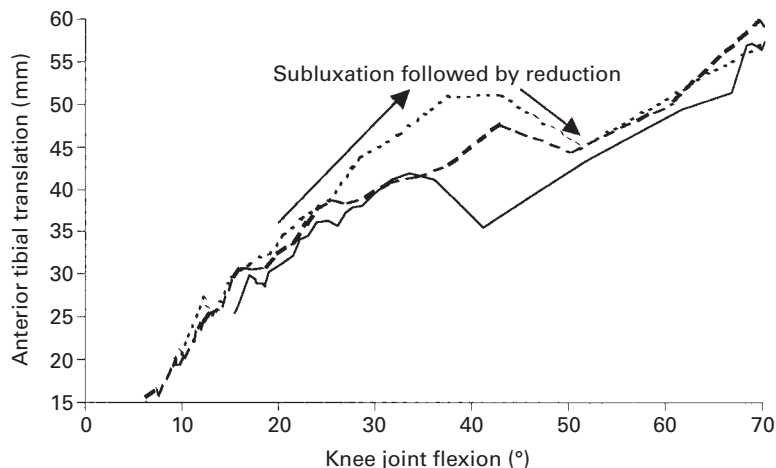


Fig. 7

Graph showing anterior translation during the pivot-shift test performed by three experienced examiners on a single subject.

or hard endpoints, which again vary with the stiffness of the joint. The tests require knowledge of the forces applied to the joint.

Although there have been mixed reports of the contribution of the ACL to tibial rotational stability, Figure 2 shows clearly that reconstruction of the ACL reduced rotational laxity significantly when the knee was flexed. In addition, as the knee approached full extension, the envelope of movement was shifted into external tibial rotation after reconstruction of the ACL. This corresponds to posterior reduction of the lateral tibial plateau, as seen with the 'before' and 'after' diagrams in Figure 6. There was a significant reduction of the pathological internal tibial rotation movement across the whole range of knee flexion measured after reconstruction of the ACL (Fig. 2).

The limits of ligamentous laxity were obtained while applying a torque to the tibia by hand, grasping the foot. A more reproducible endpoint may have been found if a known torque had been applied, but this was not feasible during surgery. Tibial rotational freedom is followed by a 'hard endpoint' as the peripheral tissues tighten. This means that, at the endpoint, an increase in torque applied to the tibia will result in very little change in rotation. Therefore, the errors arising from our method were likely to be small. It is not clear how the envelope of movement corresponds to the function of the knee, because the added loading conditions during weight-bearing could not be included in this study. Cadaver experiments by Lane et al<sup>10</sup> and Reuben et al<sup>11</sup> showed no difference with quadriceps load in the envelope of tibial rotation before and after division of the ACL. This may suggest that the effect of loading the quadriceps is to stabilise the knee. This conflicts with others who have shown a significant difference in tibial rotation after division of the ACL,<sup>12</sup> although Amis and Scammell<sup>9</sup> found no significant difference before and after reconstruction of the ACL.

For the pivot-shift test, our illustrations show that in the ACL-deficient knee the tibia subluxes anteriorly and into internal rotation at the start of knee flexion, principally due to excessive anterior movement of the lateral tibial plateau.

The 'pivot' phase is a sudden reduction of pathological laxity, which is a combined posterior translation and external rotation. The graphs show clearly how this 'sawtooth' displacement behaviour is corrected by reconstruction of the ACL. Having completed this set of measurements, we now have ethical permission to repeat this work on the intact knee, to compare it with the knee after reconstruction of the ACL.

There is little information in the literature about the kinematics of manual manipulations of ACL-deficient knees in vivo. Gillquist and Messner<sup>13</sup> used an instrumented spatial linkage to measure the kinematics of patients who had undergone reconstructive surgery. They showed clearly the difference between those knees which did not have a pivot shift and those which did. The difference was highlighted by an anterior subluxation of the tibia in early flexion followed by a reduction. Their results are very similar to ours as shown in Figure 4. They did not present the results of tibial rotation. Similar results have been presented for cadaver knees in which the ACLs were sectioned.<sup>8,11,14</sup> Noyes et al<sup>14</sup> showed that different examiners produced markedly different kinematics during the pivot-shift test on the same cadaver limb. The results presented for this one limb had a similar spread of tibial translations and rotations to those presented for ten subjects and one examiner in Figure 6. We have used a single experienced examiner in this study in order to minimise the variations possible, although to use equipment to apply reproducible loading conditions would provide better control. As part of the preparation for this study, we had a number of experienced examiners elicit the pivot shift; this showed a variation in the anterior translation of the tibia occurring at a similar angle of flexion (Fig. 7). Tibial rotation during the pivot shift was highly variable with, in some knees, no discernible 'rotatory shift'. We conclude that the pivot shift is most consistently described as a translation of the tibial plateau, rather than a rotation.

Kärrholm<sup>15</sup> described a pivot shift produced actively by a patient with rupture of the ACL. He presented the movement of the tibial plateau as in Figure 6 and showed a very

similar pattern of posterior translation of the lateral tibial plateau combined with an external rotation. This combined movement can be resolved to a rotation about a point medial to the knee. It suggests that the 'active' pivot shift correlates with the clinical test elicited by manipulation. Past work has led to the suggestion that the pivot shift occurs about the medial collateral ligament, acting as the pivot.<sup>16</sup> We suggest that this is not the case, with variable amounts of rotation and about rotational axes with variable locations. The pivot-shift reduction component positively correlates with the envelope of tibial rotation data. This would suggest that the pivot-shift manipulation imposes loads on the knee which force the knee into maximum (subluxed) internal rotation near extension and then allows the reduction of this pathological internal rotation as the knee is flexed.

This method of measuring the kinematics of joints intraoperatively has shown the change in passive kinematics achieved after reconstruction of the ACL. The effect of this change in kinematics on the function of the knee and the long-term outcome has yet to be shown. It is known that although the early outcome of this surgery may be very good, the long-term prognosis for these patients may include the development of osteoarthritis.<sup>2</sup> A tool which enables the kinematics of the joint to be adjusted intraoperatively to match the kinematics of the intact joint may provide intraoperative confirmation of a good repair and may delay or even inhibit the onset of osteoarthritis. This technique would allow intraoperative adjustment to be made, based on a clear understanding of the kinematics of the joint. This may be achieved by measuring the kinematics of the contralateral, uninjured limb, using the same intraoperative protocol at the same time as surgery on the ACL. The major unknown factor is the loading imposed by the clinician during the manipulations of the test. It is widely accepted that the pivot-shift test correlates most closely with the clinical symptoms of instability<sup>17</sup> and therefore it is desirable to make it as objective as possible.

The differences in kinematics presented by the ten subjects relate to the biomechanical differences of their knees. The soft tissues and bony geometry will have different properties, affecting the kinematics of the joint.<sup>17</sup> In order to use this technique to modify surgical procedures, full knowledge of intact, physiological, kinematics is required. This is not possible for the pathological subject. If the

contralateral limb is intact quantification of the kinematics of that limb, under the same loading conditions as for the injured limb, will allow intraoperative adjustment of the ACL graft in order to approach physiological kinematics.

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