BIOMECHANICS OF INTRA-ARTICULAR AND EXTRA-ARTICULAR RECONSTRUCTION OF THE ANTERIOR CRUCIATE LIGAMENT

A. A. AMIS, B. E. SCAMMELL

From Imperial College, London, England

Many methods of reconstruction for ACL deficiency have been described, but little is known about their biomechanical properties. We examined extra-articular (EA), intra-articular (IA) and combined (EA + IA) reconstructions in ten cadaver knees after the ACL had been ruptured by the performance of a rapid anterior drawer movement. Stability at each stage before and after rupture and reconstruction was tested by anterior drawer, Lachman, varus-valgus and tibial rotation tests.

Both IA and IA + EA reconstructions restored normal stability, while EA reconstructions improved stability but did not restore it to normal. The addition of an EA procedure to an IA procedure made no difference to knee stability. We conclude that in cases of isolated ACL deficiency there is no biomechanical basis for EA reconstruction, either alone or in addition to an IA reconstruction.

Received 10 November 1992; Accepted after revision 3 March 1993

Although many papers have described autogenous grafts for the reconstruction of the anterior cruciate ligament (ACL) using either semitendinosus tendon (Cho 1975), the iliotibial tract (MacIntosh and Darby 1976; Losee, Johnson and Southwick 1978; Ellison 1979) or the patellar tendon (Lam 1968; Alm and Gillquist 1974), there are few reports on the biomechanics of these methods.

The strength of the different tissues has been studied (Noyes et al 1984), as have the variations of graft strength with time (Butler et al 1989), the strength of graft fixation methods (Kurosaka, Yoshiya and Andrich 1987), and the measurement of anteroposterior (AP) knee laxity (Daniel et al 1985). Draganich et al (1990) and Engebretsen et al (1990) investigated the biomechanics in vitro and concluded that a lateral iliotibial band tenodesis added to an intra-articular reconstruction shared the loads on the knee. The methods used, however, made it seem unlikely that this conclusion would be valid in clinical practice.

There are two main types of autogenous reconstruction: the intra-articular (IA) and the extra-articular (EA); a combination of these is sometimes used (IA + EA). IA reconstructions act on the tibia in a similar manner to the natural ACL, but EA reconstructions act at points remote from the normal attachments, making it likely that an IA reconstruction could restore normal stability, and that an EA reconstruction could not. If such an IA reconstruction could restore normal stability, it would appear that the addition of an EA reconstruction would not necessarily result in better stability than the IA reconstruction alone. To test these hypotheses, we carried out a series of knee reconstructions in cadaver specimens and assessed their stability by tests which reflect clinical practice.

METHODS AND MATERIALS

We tested the passive capsular and ligamentous restraints with the knee intact, after rupture of the ACL, then after each of three reconstructions (IA alone, IA + EA, then EA alone), and determined any statistically significant differences in the results.

Specimens. Measurements were performed on ten human cadaver knees with a mean age of 81 years (59 to 98), obtained complete with all subcutaneous soft tissues and stored at −20°C in sealed polyethylene bags. Preparation for testing was by removal of soft tissues from the tibial and femoral shafts and mounting in steel tubes using PMMA bone cement. The tibia was centralised to ensure consistent rotational behaviour, using a jig with a pointer that passed through a central split in the patellar tendon and allowed the axis of the tube to be located between the tips of the tibial spines. The fibula was transected at its neck, and its head fixed to the tibia with two bone screws, to simulate the restraint provided by the
interosseous membrane. All tests were completed on each knee on the day that it was thawed.

**Stability tests.** Varus-valgus stability was tested at 0° and 20° flexion. The tibia was clamped horizontally and a moment of 10 Nm applied via a femoral intramedullary rod, using a 30 N weight attached by a string placed over pulleys so that the rod could be pulled medially or laterally in a horizontal direction. A pointer hanging from the rod indicated angular deflections on a scale centred at the joint.

Internal and external tibial rotation was measured at 90° flexion, using a 3 Nm torque by the method described by Amis and Dawkins (1991).

Anteroposterior drawer stability was tested in an Instron materials test machine. The femur was clamped to the base of the machine and the tibia was attached to the moving crosshead (Fig. 1) via an attachment which had four degrees of freedom of motion, allowing secondary coupled rotation and translation of the tibia during AP displacements. The tibia was moved at 50 mm/min between +150 N and −150 N for three conditioning load cycles before records were taken of force, AP displacement and internal and external tibial rotation. The tests were performed at 20° flexion to simulate the Lachman test, and at 90° for the anterior drawer test with the tibia free to rotate. The 90° test was then repeated after fixing the tibia in first internal rotation and then external rotation while applying 3 Nm of torque.

**Ligament injury.** The ACL of the specimen was ruptured in the Instron machine at 90° flexion: the tibia being displaced 30 mm anteriorly at a speed of 1000 mm/min while remaining free to move in varus-valgus angulation, medial-lateral or proximal-distal displacement and internal-external rotation. The force applied, the anterior displacement and secondary proximal displacement and rotation of the tibia were recorded. After the rupture, all stability tests were repeated.

**ACL reconstructions**

**IA reconstruction** used a central, 10 mm wide, full-thickness strip of the patellar tendon with tibial and patellar bone blocks. These were placed through bone tunnels centred accurately on the ACL attachments using a drill guide (Fig. 2). The femoral bone block was secured by a transverse 4.5 mm AO cortical bone screw, and in osteoporotic specimens this was supplemented by pouring liquid bone cement into the tunnel. The graft was tensioned by hanging a 40 N weight from the tibial bone block at 45° flexion before tibial fixation was performed by the same method.

**EA reconstruction** used an 18 mm wide strip of the iliotibial tract, which was left attached to Gerdy's tubercle. The free end was passed under the lateral collateral ligament and was secured to the femur using a
freezing device (Fig. 3). This gave secure attachment to the lateral intermuscular septum, thus simulating a healed graft. This seemed preferable to the use of sutures or spiked washers, which may have slipped under load. The device was initially attached with a bone screw and we used liquid CO₂ to produce freezing. The iliotibial tract was fixed with its slackness just removed, and with the knee at 90° flexion and neutral tibial rotation.

All the stability tests were repeated: once after the IA reconstruction; then again after adding the EA reconstruction (IA + EA); and again after cutting the IA tissue, leaving the EA reconstruction. On the first two knees, rotation and drawer tests were repeated after dividing the EA tissue, to confirm that the testing procedures had caused no changes in stability and therefore no bias from the order of testing the different reconstructions.

Student’s paired t-test for significance was used for comparisons between intact, damaged and reconstructed knees.

![Fig. 3](image)

Lateral extra-articular (EA) reconstruction, with the femur on the right and the tibia at bottom left. A strip of iliotibial tract is left attached to Gerdy’s tubercle, passed under the lateral collateral ligament and secured proximally, using a freezing device. The fibular head is secured to the tibia by two bone screws.

![Fig. 4](image)

Results of anterior drawer tests (mean and sd; n = 10) for intact, injured and reconstructed knees at 150 N, under four different conditions.

**RESULTS**

**Anterior stability**

**Intact knee.** There was no significant difference between anterior drawer tests at 20° and at 90° (p = 0.204; Fig. 4). The tibia always rotated internally as it was pulled anteriorly, by 10° ± 5° (mean ± 1sd) (Fig. 5a). The addition of fixed internal and external tibial rotation reduced anterior drawer movement significantly (p < 0.001; Figs 5 and 6), because of the tightening of the collateral structures: the medial collateral ligament resisted anterior drawer in external rotation, and the lateral collateral ligament in internal rotation.

**ACL injury.** Anterior tibial displacement caused the ACL to rupture at a displacement of 14.7 ± 6.7 mm (range 10 to 28), and a force of 673 ± 262 N (418 to 1200). As the tibia moved anteriorly it also moved proximally, by 12.8 ± 4.7 mm (4 to 19), swinging on the intact collateral ligaments. Terminal motion was resisted by rapidly increasing tension in the posterior cruciate ligament (PCL). The femoral condyles passed over the posterior horns of the menisci, but the only soft-tissue damage in addition to the ACL rupture was an occasional tear in the thin capsule anterior to the collateral ligaments. In one specimen, which was not used for the reconstruction tests, there was simultaneous rupture of the ACL and the medial collateral ligament.

**Injured knee.** Anterior drawer movement was increased significantly by our technique for cruciate rupture; this applied at both 20° and 90° flexion (p < 0.001; Figs 4 and 5b). The damaged joints were now significantly more stable at 20° than at 90° flexion (p = 0.001).

**After IA reconstruction.** After IA reconstruction, anterior drawer tests at 20° or 90° were not significantly different.
from normal (p = 0.67 and p = 0.15, respectively; Figs 4 and 5c). As in the intact knee, there was no significant difference in anterior drawer movement between 20° and 90° flexion (p = 0.39). The knees with IA reconstructions tightened in a normal manner with tibial rotation at 90°, giving stability which was not significantly different from normal values (p = 0.20 for internal rotation, p = 0.52 for external rotation; Fig. 5c).

**After IA + EA reconstruction.** For anterior stability, combined IA + EA reconstructions were not significantly different from normal (p = 0.29 at 20°, p = 0.08 at 90°), and were also not significantly different from IA reconstructions alone (p = 0.31 at 20°, p = 0.88 at 90°; Figs 4 and 5d). Stabilities in internal and external tibial rotation were also not significantly different from normal values (p = 0.17 internal, p = 0.98 external; Fig. 5d).

**After EA reconstruction.** EA reconstruction gave significantly better anterior stability than the damaged knee (p = 0.011 at 20°, p = 0.014 at 90°), but significantly less stability than normal knees (p = 0.005 at 90°; Fig. 5e). In internal rotation, the EA reconstruction tightened giving stability not significantly different from normal (p = 0.25), but in external rotation the knee remained significantly less stable than normal (p = 0.005; Fig. 5e). The EA reconstruction tightened as the knee extended to 20°, but did not stabilise the knee better than at 90° (p = 0.68): the joint remained significantly less stable to the Lachman test than normal (p = 0.001).

**Internal and external tibial rotation.** The ACL-deficient knee allowed a significantly greater amount of internal and external rotation than the intact knee (p = 0.002 and p = 0.001, respectively; Fig. 6). All three types of reconstruction restored a range of rotation that was not significantly different from normal (IA, p = 0.57; IA + EA, p = 0.74; EA, p = 0.31). IA + EA was not significantly different from the IA reconstruction alone (p = 0.39).

**Valgus-varus rotation.** The mean range of valgus-varus rotation at 20° flexion was 13° for intact knees and 14° after ACL rupture (p = 0.07). The separate valgus and varus measurements were not significantly increased by the ACL injury (p = 0.51 and p = 0.35, respectively), and all valgus and varus measurements were normal after each of the reconstructions (p > 0.47).
DISCUSSION

Our results supported our hypotheses: an IA reconstruction alone was able to restore normal stability on anterior drawer and tibial rotation testing. EA reconstruction significantly improved stability, but still left a considerable deficit from the normal. IA + EA reconstruction provided no additional stability over that achieved by an IA reconstruction alone.

In isolation, our results show no biomechanical basis for adding an EA procedure to an IA reconstruction, and no basis for using an EA reconstruction alone. The clinical reality, however, of a wide range of type and extent of injuries which include ACL rupture, means that the situation is less clear-cut than in the laboratory. Our results were obtained in elderly specimens with no stabilisation by muscles and only immediately after reconstruction. Despite these limitations, we believe that the differences which we found were clear enough to provide valid clinical guidance.

We are not aware of any previous study which has used traumatic rupture of the ACL as the starting point. Clean transection of the ACL (Draganich et al 1990; Engebretsen et al 1990) leaves the other stabilisers of the joint in a normal state, which would not be the case in a clinical rupture. This is important, since IA + EA reconstructions are considered especially in clinical situations of actual or suspected compromise of the secondary restraints.

An important decision was the displacement which should be applied to rupture of the ACL. Noyes and Grood (1976) showed that 49% elongation was required, equivalent to an elongation of 16 mm along its length. Since anterior movement of the tibia is at an angle to the line of the ACL, there is a wide range of natural laxity in different specimens (Amis 1989), and it is known that the posterior fibres are slack by 5 mm at 90° flexion (Amis and Dawkins 1991), we decided to apply 30 mm displacement to be certain of complete rather than partial rupture. After rupture, full anterior drawer movement caused the tibia to swing on the collateral ligaments, moving proximally as it emerged anteriorly from beneath the femoral condyles. This allowed large tibiofemoral displacements to occur without damage to the collateral ligaments: there was no change in valgus or varus stability in any of our specimens.

The anterior instability resulting from forcible tibial displacement of 30 mm was greater than is seen clinically, even in cases of chronic ACL deficiency, where the secondary restraints have stretched. Our experiment therefore caused definite slackening of structures other than the ACL, the so-called ‘secondary restraints’. The collateral ligaments are considered to be secondary restraints to anterior tibial displacement (Noyes et al 1980), but our results throw doubt on this since the collateral ligaments were shown not to have been stretched by the anterior tibial displacement, although large tibial translations could be produced by low forces. The implication is that the posterolateral and posteromedial capsuloligamentous tissues provide the secondary restraint to anterior drawer movement.

This difference in findings probably reflects the methods of study: ACL rupture by tibial displacement is more closely related to knee injury, whereas earlier sequential cutting studies describe the individual contributions to stability in the intact knee. In addition, Noyes et al (1980) used a ‘single degree of freedom’ test rig, in which the tibia could move only anteriorly, and not swing proximally to relax the collateral ligaments. It seems that rupture of the ACL in a test rig with many degrees of freedom provides a better basis for future experiments on ACL injury and reconstruction.

There are no accepted figures for the correct tension in grafts intended to restore normal knee stability. Burks and Leland (1988) in cadaver experiments found that 16 N in a patellar tendon graft and 61 N in an iliotibial tract graft provided normal tibial displacement at 88 N drawer force. Daniel, Penner and Burks (1988) used tensions from 4 N to 67 N to match the AP stability of the contralateral knee at operation. For our experiment we used a standard tension of 40 N, and this gave reconstructed knees which were not significantly different from normal, by our measurements.

Many types of EA reconstruction have been described, but we chose a MacIntosh type, which is typical of practice in the UK. Carson (1988) reported that no comparative study of EA reconstructions had shown
superiority for any particular one, and we therefore chose a simple rather than a complex type. In many EA reconstructions, the graft passes deep to the lateral collateral ligament, and consequently posterior to the centre of rotation of the tibiofemoral joint, causing tightening in extension. This is compatible with the aim of the reconstruction: to control anterolateral tibial displacement when the knee is near full extension, as in the pivot-shift test.

Since this EA reconstruction tends to slacken with flexion, it seems possible that it would not function well when tested at 90° flexion. We found no significant difference, however, in its action between 20° and 90° flexion. If the EA graft is overtightened the tibia is pulled into abnormal external rotation.

Many authors have discussed the ‘isometric’ placement of IA grafts in the femoral condyle; many different locations have been identified. Our 10.5 mm drill hole created an elliptical portal, approximately 11 mm by 18 mm, with little freedom of choice for its placement if it was to avoid the articular surfaces and the origin of the PCL in the root of the intercondylar notch. The graft that we used covered most of the ‘isometric’ points identified previously and gave normal knee stability.

Few authors have examined the relative clinical performance of IA and IA + EA combined reconstructions. Both Jensen et al (1983) and Strum et al (1989) found no significant difference between these methods. Roth et al (1987) reported that combined reconstructions tended to have greater anterior drawer movement, and concluded that the addition of EA reconstruction actually compromised knee stability. O’Brien et al (1991) found no significant differences but reported that 40% of the IA + EA patients reported symptoms related to the EA procedure. These clinical reports support our finding that there is no improvement when an EA reconstruction is added to an IA reconstruction. This conclusion, however, does not affect the role of EA procedures in controlling complex rotatory instabilities, such as those resulting from combined injuries of the ACL and peripheral structures affecting pivot shift more than anterior drawer.

Conclusions
1) For isolated ACL deficiency, there is no biomechanical basis for using an EA reconstruction alone, and no significant biomechanical advantage from adding an EA reconstruction to an IA reconstruction.
2) Our method of causing ACL rupture showed that great anterior instability can be produced without stretching the collateral ligaments: this throws doubt on their previously-accepted role as secondary restraints after ACL rupture.

We thank Mr N. P. Thomas for his encouragement, the Arthritis and Rheumatism Council for providing the Instron machine, and the Pathology Department of St Thomas’ Hospital for provision of 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


