BIOMECHANICS OF A DOUBLE PROSTHETIC LIGAMENT IN THE ANTERIOR CRUCIATE DEFICIENT KNEE

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We have assessed the biomechanical properties of a ‘double-bundle’ prosthetic ligament replacing the anterior cruciate in cadaver knees. We compared the results with those of single bundle ‘over-the-top’ and ‘through-the-condyle’ techniques, performing anterior drawer tests at 20° and 90° knee flexion.

The over-the-top reconstruction gave better anteroposterior stability at 20°, while the through-the-condyle repair was more stable at 90°. The double-bundle reconstruction gave practically normal anterior stability at both 20° and 90°.

Various authors have subdivided the anterior cruciate ligament (ACL). Abbott et al (1944) first mentioned a functional anteromedial group of fibres that became taut in flexion. Lam (1968) described two bundles, named anteromedial and posterolateral according to their relative tibial insertions (Fig. 1). This subdivision was supported by Girgis, Marshall and Al Monajem (1975) and Furman, Marshall and Girgis (1976). In 1979 Norwood and Cross described a third smaller, so-called intermediate bundle, and this finding was supported by Dawkins and Amis (1985). Welsh (1980) described the ACL as a continuum of fibres, without mentioning a clear anatomical distinction between the various parts.

The normal function of the ACL is more complex than could be provided by a single band of fibres; its behaviour might be modelled more closely by implants which seek to duplicate its complexity more closely. At present almost all ACL replacements have had a single strand configuration. They have been used either passed over the posterior bulge of the lateral femoral condyle as an ‘over-the-top’ (OTT) repair or else through a drill hole in the condyle as a ‘through-the-condyle’ (TTC) repair.

We could find only one previous report of a two-bundled system to reconstruct the ACL (Zaricznyj 1987), but this did not include a biomechanical assessment. Our study was therefore designed to assess the biomechanical properties of a ‘double-bundle’ reconstruction in comparison with OTT and TTC single-bundle reconstruction.

MATERIALS AND METHODS

Six human cadaveric knees with soft tissues and about 10 cm of femur and of tibia were obtained and stored in sealed polyethylene bags at −18°C.

When needed, specimens were thawed by immersion of the bags in warm water. The quadriceps tendon, patella and patellar ligament were completely excised together with most of the patellar fat pad, taking care not to disturb the peripheral attachments of the menisci, and leaving the ligamentous and capsular structures intact. This gave access to the interior of the knee and the cruciate ligaments. We have previously shown (Amis...
1989) that this dissection does not cause significant changes to anteroposterior (AP) knee stability. The fibula was divided distal to its neck, the head being fixed to the tibia by two screws to simulate the fixation normally provided by the intact interosseous membrane.

The shafts of tibia and femur were cleaned of soft tissues, including the peristeme, but preserving the attachments of the collateral ligaments. The bones were roughened with a rasp, cleaned with alcohol to remove any grease, then fixed in cylindrical metal containers by six pointed screws and polymethylmethacrylate cement.

Throughout the preparation and testing, care was taken to prevent dehydration of the soft tissues, as this has been shown to occur rapidly at room temperature and may affect the biomechanical behaviour of connective tissue (Tkaczuk 1968).

**Implants.** The implant used in all types of repair was a multifilament polyester (Terylene) prosthetic ligament, consisting of 40,000 fibres, each 15 µm in diameter, and secured by stainless steel cortical screws through loops at each end of each implant.

The OTT and the TTC repairs were inserted through a 5 mm hole in the tibia, drilled from a central point on the anteromedial tibial surface, 30 mm distal to the joint line and emerging at the anterior part of the tibial insertion of the ACL. The hole in the lateral femoral condyle was sited at the centre of the femoral origin of the ACL. Holes were placed accurately by means of a drill guide.

For the double-bundle reconstruction a second 5 mm hole was drilled in the upper tibia to emerge into the knee through the part of the ACL insertion associated with the posterolateral bundle. The anteromedial bundle was represented by a prosthetic ligament passed through the anterior hole in the tibia, then across the knee as an OTT repair. A second prosthetic ligament, representing the posterolateral bundle, was passed through the posterior hole in the tibia and through the hole in the lateral femoral condyle as a TTC repair (Figs 2 and 3).

The ligaments were tensioned manually before screw fixation, by subluxing the tibia on the femur, until it was judged that the laxity was comparable to that found for each knee with its ACL intact.

**Anteroposterior stability.** The knees were mounted in an Instron 1122 materials testing machine. The tibia was fixed horizontally into a purpose-built casing attached to the load cell on the movable crosshead, while the femur was mounted in another purpose-built holder that could be adjusted to differing degrees of AP and lateral flexion and was fixed to the base of the machine. Care was taken to ensure that no excessive loads were applied across the joint when the bolt in the crosshead-holding device was finally tightened. The crosshead moved at 50 mm/minute and automatically reversed direction when a force of 150 N was measured by the load cell in either direction. This maximum load was chosen as it corresponds to loads imposed on the ACL when walking (Morrison 1969). A graph plotter drew curves of force against displacement during the test. Errors due to deflections of the bones in their rigid mountings were considered to be negligible at the relatively small forces used in this study, so tibiofemoral subluxation was taken to be equal to crosshead movement.

**Stages of testing.** In clinical practice, it is customary to test for ACL laxity at 20° of knee flexion (the Lachman test) and again at 90° (the anterior drawer test), so anteroposterior movement was measured at both angles at all stages.

Each knee was tested for AP stability in neutral, then internal and then external rotation at the following stages:
1) with the ACL intact,
2) with the ACL excised,
3) with a single ACL prosthesis as a TTC repair,
4) with a single ACL prosthesis as an OTT repair, and
5) with a double-bundle ACL prosthesis.

**Fig. 2**
Anterior view of a right knee showing the double-bundle prosthetic ligament in place.

**Fig. 3**
Posterolateral view of the double-bundle prosthetic ligament exposed by removal of the medial femoral condyle. The posterior cruciate ligament is still in situ.
Thus, 30 tests were done on each specimen. For the tests in internal and in external rotation, the tibia was rotated manually to a point where ligamentous resistance was felt.

RESULTS

The mean values of the tension phases for the ACL and posterior cruciate ligament (PCL) were calculated and plotted. These curves for the neutral position of rotation at 20° and 90° flexion are shown in Figures 4 and 5. The anterior displacement of the tibia with respect to the femur at its resting position (no force applied) for each test was measured from the graphs: the mean values are shown in Table I, and in histogram form in Figures 6 and 7. The total AP movement of the tibia is shown in Table II. Statistical analysis of the anterior displacement was carried out for each stage and compared to the intact ACL, using the paired Student's t-test (Table III).

AP stability intact ACL. There was a wide range of behaviour for the intact ACL. In neutral rotation with the knee flexed 20°, the total AP displacement of the tibia with respect to the femur at 150 N drawer force was 10.0 mm (± 1.5 mm SD, Table II). The anterior displacement (representing the ACL part of the curve) was 4.5 mm ± 0.8 mm (Table I). At 90° flexion the total displacement was 8.7 mm ± 1.4 mm and the anterior component was 4.6 mm ± 1.1 mm.

The total AP laxity (ACL plus PCL) at 20° was significantly greater than that at 90° (p < 0.02, Student's paired t-test). However, for anterior laxity alone (ACL), this difference was not significant (p > 0.05).

Internal rotation of the tibia on the femur caused a decrease in the overall AP laxity (7.3 mm at 20° and 7.5 mm at 90°); external rotation had a similar effect (8.5 mm at 20°; 8.2 mm at 90°). However, paired t-tests showed that internal rotation of the tibia caused a significant decrease in total AP drawer at 90° (p < 0.05), but not at 20° (p > 0.1), while external rotation caused a significant decrease in AP drawer at 20° (p < 0.05), but not at 90° (p > 0.5). The difference between AP drawer movement at 20° and 90° was not significant in either internal (p > 0.5) or external rotation (p > 0.05).

ACL-deficient knee. When the ACL had been completely divided, laxity increased significantly at both 20° and 90° flexion, especially when the knees were tested in mid-rotation (p < 0.001), but to a lesser extent when in

Table I. The anterior displacement of the tibia (in mm) with respect to the femur for an anterior force of 150 N, at 20° and 90° flexion, with the tibia in neutral (N), internal rotation (IR) and external rotation (ER). Results are given as mean, standard error of the mean (SEM) and standard deviation (SD)

<table>
<thead>
<tr>
<th></th>
<th>ACL Intact</th>
<th>ACL Divided</th>
<th>OTT*</th>
<th>TTC*</th>
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</thead>
<tbody>
<tr>
<td>20° N</td>
<td>4.5 ± 0.3</td>
<td>4.3 ± 0.3</td>
<td>6.9</td>
<td>3.6</td>
</tr>
<tr>
<td>SEM</td>
<td>0.3</td>
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<tr>
<td>SD</td>
<td>0.8</td>
<td>2.4</td>
<td>1.3</td>
<td>2.6</td>
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<tr>
<td>90° N</td>
<td>4.6 ± 0.5</td>
<td>8.4 ± 0.5</td>
<td>5.8</td>
<td>3.6</td>
</tr>
<tr>
<td>SEM</td>
<td>0.5</td>
<td>0.9</td>
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<td>1.2</td>
<td>1.3</td>
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<tr>
<td>20° IR</td>
<td>3.6 ± 0.3</td>
<td>4.4 ± 0.3</td>
<td>6.1</td>
<td>3.2</td>
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<tr>
<td>SEM</td>
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<td>0.9</td>
<td>0.5</td>
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<tr>
<td>SD</td>
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<td>2.2</td>
<td>1.3</td>
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<tr>
<td>90° IR</td>
<td>3.4 ± 0.3</td>
<td>4.5 ± 0.3</td>
<td>4.1</td>
<td>2.2</td>
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<tr>
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<td>0.4</td>
<td>0.6</td>
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<td>SD</td>
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<td>1.6</td>
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<tr>
<td>20° ER</td>
<td>3.4 ± 0.3</td>
<td>4.4 ± 0.3</td>
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<tr>
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<tr>
<td>SD</td>
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<td>1.9</td>
<td>1.4</td>
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<tr>
<td>90° ER</td>
<td>4.1 ± 0.3</td>
<td>7.4 ± 0.3</td>
<td>5.5</td>
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<td>SEM</td>
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* OTT, over the top; TTC, through the condyle

Fig. 4

Mean force-displacement curves at 20° (left) and 90° (right) for the intact ACL, the ACL divided, the OTT, TTC and double-bundle reconstructions. The PCL curve (lower left quadrant) was unchanged throughout.
Table II. The total anteroposterior displacement (in mm) of the tibia with respect to the femur for anterior and posterior forces of 150 N, at 20° and 90° with the tibia in neutral (N), internal rotation (IR) and external rotation (ER). Results are given as mean, standard error of the mean (SEM) and standard deviation (SD).

<table>
<thead>
<tr>
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<th>ACL Intact</th>
<th>ACL Divided</th>
<th>OTT*</th>
<th>TTC*</th>
<th>Double bundle</th>
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<tr>
<td>90° N</td>
<td>8.7</td>
<td>16.9</td>
<td>12.5</td>
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<tr>
<td>SD</td>
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<td>4.7</td>
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<tr>
<td>90° IR</td>
<td>7.5</td>
<td>11.3</td>
<td>8.6</td>
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<td>SD</td>
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<td>2.8</td>
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<tr>
<td>20° ER</td>
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<td>16.3</td>
<td>9.5</td>
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* OTT, over the top; TTC, through the condyle.

rotated positions (Tables I and III). The total anteroposterior laxity at 20° (19.6 mm) and at 90° (16.9 mm) were not significantly different (p > 0.05).

OTT reconstruction. After an OTT repair, laxity increased when the knee was flexed from 20° to 90°, the converse result to that of the OTT repair. TTC repairs were significantly less stable than the normal ACL at 20° (p < 0.05), but not significantly different at 90°.

TTC reconstruction. After TTC reconstruction, AP laxity decreased when the knee was moved from 20° to 90°, the converse result to that of the OTT repair. TTC repairs were significantly less stable than the normal ACL at 20° (p < 0.05), but not significantly different at 90°.

Double-bundle reconstruction. The curves for the double-bundle reconstructions (see Figs 4 and 5) show that anterior laxity did not differ between 20° and 90° flexion (Table I), and that these displacements were not significantly different from those for the intact ACL (Table III). This remained true in internal and in external rotation.

The anterior displacements for each of the three methods for replacing the ACL are summarised in Figures 6 and 7, which also show the standard error of the mean.

DISCUSSION

The primary function of the ACL is to resist anterior displacement of the tibia with respect to the femur (Brantigan and Voshell 1941; Marshall et al 1975; Wang, Rubin and Marshall 1975).

The force-displacement curves we obtained at 90° for the intact knee are similar to those reported by Butler,
Noyes and Grood (1980) and Piziali et al (1980). The better AP stability of the intact knee at 90° and the statistically significant difference between total AP laxity at 20° and 90° has been reported previously (Amis 1989); this supports the clinical observation by Gurtler, Stine and Torg (1987) that Lachman's test is a more sensitive indicator of ACL rupture than the anterior drawer test. However, this difference was effectively abolished when the tibia was internally or externally rotated on the femur.

As expected, transection of the ACL caused a significant increase in anterior laxity, but the difference between these laxities at 20° and 90° was not significant.

The OTT and TTC reconstruction methods were shown to have differing actions depending on the degree of knee flexion. The OTT repair slackened in flexion, while the TTC slackened in extension. This was true in neutral, internal or external rotation (Figs 6 and 7). Only the double-bundle repair conferred similar AP stability at both 20° and 90°.

The force-displacement curve for the double-bundle repair lies to the left of the curve for the intact ACL, but it has been shown (Amis 1989) that shifting of force-displacement curves to the left and right on such a graph is due to over-tensioning and under-tensioning respectively, and that small changes of implant tension caused significant differences in stability and range of motion. Therefore, had the double-bundle reconstructions been inserted with less tension, they would have mimicked the intact ACL even more closely. Slackening of the anchorage by 1 mm would have given curves indistinguishable from those for the normal ACL. This adjustment in tension could also have been performed for the single-bundle reconstructions, but it would not have been possible to mimic the intact ACL at both 20° and 90° because of the changes in laxity between these angles. Perfect adjustment of implant tensions would not change the main finding of this work: the double-bundle reconstruction, unlike the OTT and TTC methods, confers and maintains near normal anterior stability at both 20° and 90° of knee flexion.

The effect of internal or external rotation is shown in Figures 6 and 7. In general the relationship of the curves to each other remained unchanged, but there was a universal reduction in anterior laxity when compared with mid-rotation. The reduction was less marked in external than in internal rotation and is known to be due to tightening of the secondary restraints: lateral ligament and capsular structures in internal rotation, medial structures in external rotation (Noyes et al 1980). For the intact ACL, this decrease in laxity was statistically significant (p < 0.05). The OTT implant gave more stability than the TTC in internal and external rotation at 20°, while the TTC was more stable at 90°. The double-bundle implant maintained stability at both degrees of flexion in internal and external rotation.

The double-bundle method we used differed from that described by Zaricznyj (1987). He treated 14 patients with a double semitendinosus autograft, passed through two holes in the tibia, as in our study. However, Zaricznyj routed both components through a single hole in the lateral femoral condyle. He considered that the double configuration served two purposes: first, to duplicate the anatomical insertion of the ACL on the tibia, and secondly, to increase the strength of the repair. At a mean follow-up of 3.6 years, using a standard scoring system (Marshall, Fetto and Botero 1977), 12 of his patients were rated as excellent or good and two as fair. Unfortunately no biomechanical data are available for comparison.

Instability depended, of course, on the exact site of attachment of the implants to the bones. It is known that changes in position of the femoral drill hole, in particular, affect the lengths of prosthetic ligaments during movement (Bradley et al 1988). It has been suggested that the femoral drill hole could be placed specifically to give isometric behaviour; this is believed by some (Chapman 1987; Penner et al 1988) to be advantageous for TTC reconstructions and might give better results.

We did not attempt this for several reasons: although the attachment of a thin thread to replace the ACL may identify an 'isometric point', knee movement is not then normal; the isometric point, if this exists, is lost somewhere within the bulk of a real implant as it emerges from a 6 to 9 mm hole with radiused edges. The centre of the ACL origin is between the anteromedial and the posterolateral bundles, and these are known to have reciprocal length changes during flexion/extension (Dawkins and Amis 1985); the natural ACL as a whole has varying tightness during flexion/extension (Kennedy, Weinburg and Wilson 1974).

Furthermore, the location of an 'isometric' point is controversial among those claiming to have identified it: Penner et al (1988) located it in the origin of the anteromedial bundle, Odensten and Gillquist (1985) in the intermediate bundle origin (the site of TTC drill holes in our study), and Sidles et al (1988) against the roof of the notch, outside the origin of the ACL.

A further consideration in favour of a double-bundle implant, as against even an 'ideal' isometric bundle, is that the latter will be tensed continuously, predisposing it to creep and hence slacken. The reciprocal tightening/slackening of the double bundles in flexion/extension allows part of the implant to relax while, at the same time, the knee is always kept stable.

This laboratory study has produced some interesting results, but the clinical use of such implants would entail some complex surgery. We have started some animal work to provide more evidence. Recognising that ligament replacement is still in its infancy, we hope that the development of implants more like the natural structures will be a fruitful line of research work.

Conclusions
1) An OTT repair functions like an intact anterior cruciate ligament at 20° of knee flexion.

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2) A TTC repair functions like an intact anterior cruciate ligament at 90°.
3) A double-bundle repair approximates in function to the intact anterior cruciate ligament at both 20° and 90° and merits further investigation.

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REFERENCES