Fixation of the graft in reconstruction of the anterior cruciate ligament

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Methods of reconstruction of the anterior cruciate ligament (ACL) have developed considerably over the last 15 years. Primary repair and extra-articular procedures have failed to reproduce satisfactory stability of the knee and the use of prosthetic ligaments has been abandoned. These techniques have been superseded by reconstruction with an intra-articular graft. The current surgical approach is by anatomical reconstruction using a biological tissue autograft. The bone-patellar tendon-bone graft (B-PT-B) has given good clinical results, but morbidity at the donor site has prompted many surgeons to favour the four-strand hamstring graft usually using the tendons of semitendinosus and gracilis doubled.

Reconstruction should aim to recreate the exact mechanical properties of the injured ligament and restore normal function to the knee. Currently, this cannot be achieved.

Biomechanical testing of ligament reconstructions in the laboratory has been used widely in attempts to recreate these mechanical properties. The ultimate load to failure of the B-PT-B graft has been shown to be 2977 N and that of the four-strand hamstring graft 4140 N. These values both exceed those reported for the intact ACL. The stiffness of the graft construct is partly determined by the choice of fixation and also by the effect of cyclical loading. These are therefore probably more important considerations. Many surgeons now appreciate that in the early post-operative period it is the fixation of the graft, particularly when using the hamstrings, which is the weak link, a point originally emphasised by Kurowska, Yoshiya and Andrish.

Fixation may be either mechanical or biological. The emphasis on accelerated programmes of rehabilitation and demands for a rapid return of function necessitate secure mechanical fixation in the early post-operative period before biological fixation has occurred by healing in the graft tunnel.

This article reviews our current knowledge of the options available for fixation of the graft.

The anatomy and mechanical properties of the ACL

An appreciation of the anatomy and mechanics of the ACL is important if its structural properties are to be reproduced. The ligament originates from the medial aspect of the lateral femoral condyle and is inserted into the tibial plateau medial to the anterior horn of the lateral meniscus. It is a single continuum of fibres which has sometimes been separated into anteromedial and posterolateral bundles depending on the attachments of the fibres to the tibia. It has a mean length and cross-sectional area of 44 mm and 27 mm, respectively. Laboratory investigation of the ultimate load to failure and stiffness of the ACL gives typical values of 2160 N and 242 N/mm, respectively (Table I).

Marked variations in values are reported depending on the age of the cadaver specimens used. Woo et al gave figures which were 25% to 30% higher than those of previous studies probably because of differences in orientation of the specimen during testing. They also showed that the ACL is two to three times stronger in the third than in the eighth decade of life.

Daily tensile loading of the normal ACL has been estimated to be no more than 20% of its ultimate load to failure. Holden et al examined the forces in the knee during various activities and calculated those in the muscles and ligaments. The maximum forces calculated in the ACL were during walking down a ramp, reaching 445 N. The load on the ACL during level walking reached 169 N.

Biological fixation

The normal attachments of tendons and ligaments are either direct or indirect. A direct attachment comprises a four-layer interface of tendon, fibrocartilage, mineralised fibrocartilage and bone. This transmits tensile forces well and is present at the tendon-bone interface of a B-PT-B graft. The progressive
increase in tissue stiffness reduces stresses at the site of attachment of the ligament. An indirect attachment links the ligament or tendon by fibres to the periosteum. This is achieved by Sharpey’s fibres, characteristic of this type of insertion.23,24

**Bone-patellar tendon-bone grafts.** The sequence of healing of a B-PT-B graft within a bone tunnel was studied histologically in a canine model.24 At the bone-bone interface incorporation of the bone plug at each end of the graft was completed by 12 weeks. The original tendon attachment of the graft maintained the features of direct attachment throughout the healing processes. By 12 weeks there were Sharpey-like fibres at the interface between the patellar tendon and the host bone tunnel. Similar conclusions were drawn from a study in Rhesus monkeys.25 The structure of the graft-bone interface resembled that of the normal ACL.23

**Hamstring grafts.** Most studies report appearances consistent with indirect healing of hamstring grafts.26-30 In a study of digital extensor tendons sutured into bone in dogs, collagen fibres were seen between the tendon and the wall of the bone tunnel at four weeks.26 Sharpey’s fibres were identified at 12 weeks and were mature at 26 weeks. Failure of the graft by pull-out from the bone tunnel occurred up to eight weeks, but by 12 weeks such tests showed adequate fixation at the graft-bone interface when the graft itself failed. A study of the biomechanical and histological changes in a rabbit model27 showed adequate fixation at the interface between the semitendinosus and the tunnel at three weeks. Fixation was indirect by Sharpey’s fibres. Pinczewski et al28 studied specimens from two patients undergoing revision surgery after mid-substance rupture of an ACL graft. The grafts had been fixed by interference screws. Histological examination at 12 and 15 weeks showed continuity of the collagen fibres between the bone tunnel and the tendon resembling Sharpey’s fibres. They suggested that the tight contact between the bone and graft achieved by an interference screw was important for integration of the graft. However, similar histological appearances of healing have been reported with endobutton fixation of hamstring grafts.29 A recent study by Weiler et al30 challenges this view. A histological and biomechanical study of tendon healing in a bone tunnel after biodegrad-

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**Table I. Graft strengths**

<table>
<thead>
<tr>
<th>Authors</th>
<th>Graft*</th>
<th>Ultimate failure load (BN)</th>
<th>Stiffness (N/mm)</th>
<th>Specimen age (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woo et al8</td>
<td>Intact ACL</td>
<td>2160</td>
<td>242</td>
<td>22 to 35</td>
</tr>
<tr>
<td></td>
<td>Bone-patella-bone graft</td>
<td>2977 (10 mm graft)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cooper et al6</td>
<td>Hamstring graft (DLSTG)</td>
<td>4213</td>
<td>954</td>
<td></td>
</tr>
<tr>
<td>To et al9</td>
<td>Semitendinosus graft</td>
<td>4140</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

* ACL, anterior cruciate ligament; DLSTG, double-looped semitendinosus and gracilis

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**Fig. 1**
Free tendon end held in freezing clamp of materials testing machine.

**Fig. 2**
Specimen set up in materials testing machine with tibial bone tunnel in line with loading axis.
able interference screw fixation in sheep showed evidence of direct-contact healing at the tendon-bone interface. Anatomical fixation by interference screws may promote direct healing and aid incorporation of tendon and bone.\textsuperscript{30}

**Laboratory testing**

Biomechanical testing has been applied particularly to different types of graft fixation.\textsuperscript{31} Testing gives an assessment of how closely a construct’s biomechanical performance will match that of the normal ACL immediately after surgery. It allows prediction of the vulnerability of a particular fixation to failure under post-operative rehabilitation and provides an environment for direct comparison of different techniques and fixation devices. Studies usually involve reproducing either the tibial\textsuperscript{32} or femoral sides of a reconstruction, but may include tests performed on complete constructs.\textsuperscript{33,34}

Using a materials-testing machine, loads can be applied either to the free tendon end of the reconstruction (Figs 1 and 2) or to the whole knee if a complete construct is being tested. The apparatus usually allows multiaxial adjustments so that the direction of force applied to the graft can be adjusted. The orientation of the specimen\textsuperscript{8} and the type of bone specimen used are the most important variables influencing the test results.

**Orientation of the specimen.** In a cadaver study\textsuperscript{8} of the tensile properties of the human femur-ACL-tibia complex, anteroposterior displacement tests were applied with the intact knee at 30° and 90° of flexion. The angle of knee flexion had a significant effect on the results. In the same study, tensile tests were performed on the femur-ACL-tibia complex with the knee flexed to 30°. One knee from each pair of cadavers was orientated anatomically and the other aligned with the tibia angled vertically. Higher levels of stiffness and ultimate load were recorded in the specimen which was orientated anatomically. Although this study was performed on intact human ACL specimens and not reconstructions, it illustrates how orientation can affect the results of biomechanical tests. In many studies, including ours, forces are applied in the axis of the bone tunnel.\textsuperscript{35,36} This transfers the greatest force to the point of fixation of the graft and provides a ‘worst-case scenario’. This should not bias comparisons of similar fixations but it does not accurately reproduce forces experienced \textit{in vivo}.

**Choice and preparation of specimens.** The availability of young human knees to provide test models is often limited. Consequently, many studies have been performed using porcine or bovine knees. It is not clear whether these specimens give an accurate model of the young human knee. A study by Brown et al\textsuperscript{37} found that young bovine knees provided a more clinically relevant model of a young human knee than did elderly human cadaver knees. This has prompted many investigators to use young bovine knees as a test model.\textsuperscript{9,10,38-41} However, a number of studies have now questioned the validity of this. Magen et al\textsuperscript{32} compared six methods of tibial fixation in both animal and young human bone. Interference screws performed well in animal tissue but failed at loads below 500 N in young human bone. The authors recommended that animal tissue should not be used to estimate the performance of fixation by interference screws in human tissue.

The age of human cadaver specimens is also an important factor. In studies performed by Woo et al\textsuperscript{8} and Noyes et al\textsuperscript{15} the biomechanical properties decreased in older specimens. These biological variations can be explained by differences in the bone mineral density (BMD) and microstructure. A study by Brand et al\textsuperscript{40} examined the effects of BMD on fixation of hamstring grafts using interference screws. The BMD of human knees was measured using dual-photon absorptiometry and was found to be greater in the metaphysis of the femur than in that of the tibia. The ultimate load to failure was directly related to the BMD of both the tibia and the femur.

**Parameters measured.** Historically, most studies have concentrated on measuring the ultimate load to failure of a particular construct or fixation device. By extending the specimen at a chosen rate, a load versus elongation curve can be plotted. From this the stiffness of the bone-graft-bone construct can be determined.\textsuperscript{31}

Increasing the stiffness and tension of a reconstruction at the time of implantation may constrain the knee. Conversely, decreasing them may result in excessive laxity. In a series of tests on different femoral fixations, To et al\textsuperscript{9} showed that they were between four and 40 times less stiff than the double-looped gracilis and semitendinosus graft used in the study. They concluded that an increase in stiff-
The variability and complexity of the methods of study used and of the biological specimens make it difficult to compare different techniques of fixation directly, and recommendations have been published in an attempt to standardise this.\textsuperscript{31} Forces are applied repetitively to the reconstruction using a materials-testing machine and the resulting elongation is measured. This represents slackening or stretching of the graft.

The latter may be determined by applying incremental loads to the construct until failure and measuring the differences between the original length and that after the applied load. Although the ultimate load to failure may represent a catastrophic event such as a fall, it does not reproduce the type of repetitive loading experienced during aggressive post-operative rehabilitation programmes. Cyclic load testing has been adopted by many in an attempt to address this.\textsuperscript{8,10,35,36,42,43}

### Mechanical fixation

Methods of mechanical fixation can be categorised as either direct or indirect. Direct methods such as interference screws, staples and spiked washers compress the graft against the outer surface of the bone or the wall of the bone tunnel (Fig. 3). Indirect fixation as with cross-pin fixation and endobuttons suspend the graft within the bone tunnel.
In discussing methods of fixation it is vital to distinguish between the tibial and femoral sides. The decreased BMD in the tibial metaphysis compared with the femoral side has particular relevance to the fixation of interference screws as noted previously.

Fixation of a bone-patellar tendon-bone graft

Interference screws. Fixation by an interference screw stabilizes the graft close to the joint line and to the sites of attachment of the active ACL. Juxta-articular fixation has been shown to reduce anteroposterior translation. Interference screws also compress the bone block of the graft against the tunnel wall allowing direct graft-tunnel healing.

The biomechanical advantages of screw fixation were described by Kurosaka et al in a comparative study of different methods of fixing B-PT-B grafts. Investigations have shown favourable biomechanical properties with fixation in both the tibia and femur using both metal and bioabsorbable screws (Tables II to IV).

Press-fit fixation. Stabilisation of the graft in the femur and/or tibia without interference screws using a press-fit technique has been advocated in order to avoid the potential complications associated with their use. Removal of the implant is not required in revisions. Biomechanical studies report favourable fixation and the clinical results at two to five years appear to be satisfactory, although concerns over the quality of fixation have been raised in one paper.

Screw/screw-washer post fixation. Sutures tied over a screw used as a post with or without a washer are predominantly used on the tibial side of the reconstruction when there is a mismatch of the graft and the tunnel. Most studies have shown inferior stiffness and load to failure of the construct.
compared with the use of interference screws.11,49 This indirect form of fixation lies further from the joint line and does not give the benefits of graft compression within the bone tunnel.

**Staples.** These provide an alternative form of direct tibial fixation with B-PT-B grafts where there is a mismatch between the graft and tunnel. In one study biomechanical comparison of different methods of fixation of B-PT-B grafts showed an inferior ultimate load to failure when compared with screw/post fixation.11 The stiffness of the construct was similar, but in both techniques was significantly inferior to that achieved with a 6.5 mm cancellous interference screw. However, it is not clear whether tests were carried out on tibial or femoral specimens.

**Endobutton.** In B-PT-B graft reconstruction, fixation with an endobutton is usually used only in the presence of a blow-out of the posterior femoral wall.50 Although this fixation includes a length of linkage material between the button and the graft, the stiffness of the fixation is acceptable. However, this suspensory type of fixation is distant from the joint line, a factor which has been associated with increased anterior joint laxity.42

**Cross pins.** In an effort to try to avoid graft slippage, cross pins have been introduced. These are usually biodegradable pins 2 to 3 mm in diameter, that pass across the bone and through the thickness of the bone plug. They have been found to provide similar fixation to the interference screws.51 However, if the B-PT-B bone plug was less than 9 mm wide, it was found that it fractured at a lower load.

**Fixation of a hamstring graft**

Direct methods of fixation of a hamstring graft reconstruction on the femoral side include interference screws and a claw washer-screw combination. Indirect methods are by endobutton, transverse pin fixation and anchors within the tunnel with graft suspension loops. Tibial fixation may be achieved directly by interference screws, staples, a screw and washer or a clawed washer and screw. Indirect fixation with sutures and the use of a screw as a post is another option.

### Table IV. Hamstring tibia graft fixation options

<table>
<thead>
<tr>
<th>Authors</th>
<th>Hamstring tibia Specimen</th>
<th>Test protocol</th>
<th>ULF (N)*</th>
<th>Stiffness (N/mm)</th>
<th>Cyclic testing (mm)</th>
<th>Mode of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magen et al52</td>
<td>Animal/human – not specified</td>
<td>Pull in line of tibial tunnel</td>
<td>821†</td>
<td>200 (a) 0.23 (b) 0.81</td>
<td>-</td>
<td>50 N increments-slippage (mm) at 250 N(a), 500 N(b)</td>
</tr>
<tr>
<td>Tandem washers</td>
<td>1375</td>
<td>248 (a) 0.49 (b) 1.23</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sutures/posts (No 5 ethibond)</td>
<td>830</td>
<td>259 (a) 1.67 (b) 4.87</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Staples</td>
<td>705</td>
<td>60 (a) 1.01 (b) 3.31</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interference screw (9 x 25 mm)</td>
<td>776</td>
<td>118 (a) 0.25 (b) 0.72</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiked 20 mm washer</td>
<td>930</td>
<td>226 (a) 1.12 (b) 3.52</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Giurea et al10</td>
<td>Stirup</td>
<td>Bovine</td>
<td>Tibia – pull in line of tunnel</td>
<td>898</td>
<td>-</td>
<td>150 N elongation 2.1 mm 450 N intact</td>
</tr>
<tr>
<td>Nagarkatti et al100</td>
<td>Bio-absorbable screw</td>
<td>Porcine</td>
<td>Anatomical graft placement – vertical load</td>
<td>408</td>
<td>69</td>
<td>0 to 150 N 5000 cycles 1.3 mm displacement 2 of 5 failures before 5000 cycles</td>
</tr>
<tr>
<td>Kousa et al101</td>
<td>Washerloc</td>
<td>Porcine</td>
<td>Tibia – load applied along drillhole axis</td>
<td>975†</td>
<td>917 after cyclical loading</td>
<td>1500 cycles 50 to 200 N</td>
</tr>
<tr>
<td>Spiked washers</td>
<td>769</td>
<td>675</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrafix</td>
<td>1332</td>
<td>1309</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bioscrew</td>
<td>612</td>
<td>567</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coleridge and Amis53</td>
<td>Bovine</td>
<td>RCI</td>
<td>Tibia – pull in line of tunnel</td>
<td>491</td>
<td>1.3</td>
<td>1000 cycles 70 to 220 N slippage (mm)</td>
</tr>
<tr>
<td>Delta screw</td>
<td>641</td>
<td>1.15</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrafix</td>
<td>543</td>
<td>0.69</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bicortical screws</td>
<td>770</td>
<td>1.17</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washer loc</td>
<td>946</td>
<td>0.88</td>
<td>-</td>
<td></td>
<td></td>
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</tbody>
</table>

* ULF, ultimate load to failure
† yield loads

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**Table IV. Hamstring tibia graft fixation options**
**Interference screws.** These give direct fixation of a soft-tissue graft within a bone tunnel and have been developed using a variety of materials.\(^{52}\) The method has a number of advantages.

Juxta-articular fixation of the graft has been shown to increase stability of the knee when compared with implants which fix the graft further from the surface of the joint.\(^{42}\) The screws compress the graft against the walls of the bone tunnel enhancing tendon-bone healing.

However, biomechanical testing of fixation by interference screws has shown failures of fixation during cyclical loading of the hamstring construct.\(^{10,36}\) This has raised concerns regarding aggressive rehabilitation of hamstring grafts fixed by interference screws.\(^{56}\) By harvesting the graft with a distant attachment of tibial bone the initial pull-out strength of a hamstring tendon graft fixed by an interference screw can be increased significantly.\(^{47}\) Compression of the hamstring tendons with a sheath into which an interference screw is inserted is a further development.\(^{53}\) In spite of these concerns a clinical comparison between hamstring and B-PT-B reconstructions has shown no differences between the groups as regards stability, range of movement and general symptoms.\(^{3}\)

**Claw washer/screw.** A clawed-washer-and-screw combination gives fixation distant from the joint line. The ultimate load to failure in bovine femora was 502 N,\(^{10}\) which was stronger than that of a round-headed interference screw (445 N), but less than that of a ‘soft’ interference screw (691 N).

The clawed washer performed poorly under cyclical loading and failed by slipping and shredding the tendon.\(^{10}\)**Endobutton.** This is preferred by many surgeons for femoral fixation. Sagittal and longitudinal movement in the graft tunnel under cyclical loading has raised concerns about this technique. The ‘bungee’ effect describes movement of the graft along the bone tunnel and has been implicated in widening of the tunnel\(^{54,55}\) and in inhibiting tendon-bone healing.\(^{56}\) In a cadaver study, graft-tunnel movement of 1 to 3 mm occurred under loading forces of 100 to 300 N.\(^{54}\) Cyclic elastic stretching under load can be expected to increase with lengthening of the graft between the points of fixation. Anchoring the graft distant to the joint line may also allow anteroposterior movement described as the ‘windscreen-wiper’ effect after widening of the tunnel.

A study comparing widening of the tunnel in ACL reconstructions using four different techniques of fixation showed less widening in those fixed by endobuttons compared with stabilisation by interference screws.\(^{57}\) Widening of the tunnel cannot be attributed simply to mechanical effects and probably involves a biological component.**Bone anchor.** There are several types of anchor which are inserted up to the end of a blind tunnel such as intrafix anchors in which the graft is suspended from a loop on their tail.

**Transfixation pin.** Suspensory femoral fixation by single or multiple cross pins has performed very favourably in laboratory testing. The ultimate load to failure of a 70 mm pin was as high as 1600 N in the pig femur.\(^{58}\) A construct involving femoral fixation by cross pins and anchorage at the tibia with a staple performed as well as a B-PT-B graft reconstruction fixed by interference screws.\(^{57}\) The clinical outcome of a small series using this system compared favourably with that of other reconstructions.\(^{59}\)

**Staples.** Concern over tibial fixation using an interference screw has prompted the use of alternative methods such as staples in isolation or in combination with interference screws. In a comparative study of six methods of tibial fixation,\(^{32}\) although the yield load of double staples was comparable with that of interference screws, stiffness was diminished by a factor of three and slippage of the graft under cyclic loads of 250 N and 500 N was significantly greater. Three patients developed subcutaneous pretibial ganglia after reconstruction of the ACL with grafts fixed by staples. These communicated directly with the tibial tunnel.\(^{60}\) This suggests lack of incorporation in an area of the bone tunnel with this type of anchorage.

**Screw and washer.** The Washerloc system (Arthrotek; Biomet Inc, Warsaw, Indiana) provides fixation by compression of the graft against cortical bone with a pronged washer and screw. In a comparative study the stiffness (200 N/mm) and yield load (821 N) of the Washerloc were similar to those obtained with an interference screw.\(^{32}\)**Screw post and sutures.** The free sutures from the tibial end of the graft can be secured by tying them around a screw which is used as a post. Different suture materials have different mechanical properties.\(^{61}\)

**Interference screws**

Various parameters have been shown to influence fixation by an interference screw. These include the length and diameter of the screw, its divergence, the size of the bone block compared with that of the tunnel, the geometry of the bone block, the torque of insertion of the screw, the BMD. The length of the screw. The significance of the length of the screw in interference fixation of a B-PT-B is uncertain.\(^{62-66}\) In a study comparing the strength of fixation of endoscopically inserted and ‘rear-entry’ screws, no difference was found between screws which were 20 mm and 25 mm long.\(^{62}\) Studies on porcine tibiae found no significant difference in displacement, load to failure and stiffness between interference screws of length 12.5, 15 and 20 mm.\(^{63}\)

Pomeroy et al\(^{64}\) studied the effect of interference fit on different lengths of bone plugs with interference screws and showed no difference in fixation with longer plugs. However, Gerich et al\(^{67}\) showed a significantly higher load to failure with a 9 x 30 screw compared with a 7 x 30 screw in young human cadaver knees, and Kao et al\(^{68}\) showed an increase of 79% in the ultimate load to failure of a 15 x 9 mm metal interference screw compared to one of 20 x 7 mm.

Many studies have investigated the effect of the length of the screw in hamstring reconstructions. Cyclical load test-
ing using human tibiae failed to show superior fixation of the graft with longer screws, although in another study there was a trend towards better fixation with a longer screw.

**Diameter and geometry of the screw.** Investigation of the influence of the geometry of biodegradable screws on fixation of the hamstrings showed that increasing the length of the screw improved fixation and that this was more important than increasing the diameter, presumably because the additional length provided a greater available area of thread.

The relationship between the diameter of the screw, the size of the bone block, the diameter of the bone tunnel and the fixation of B-PT-B grafts has been investigated in many studies. Fixation may be enhanced by the use of circular bone plugs rather than the trapezoidal blocks favoured by many. In the porcine tibia, no advantage was conferred by an interference screw of 9 mm compared with one of 7 mm with gap sizes (the available space between the bone block and tunnel wall), of 1 or 2 mm. However, a 9 mm screw gave superior fixation with larger gap sizes of 3 or 4 mm. Studies in bovine specimens with gap sizes of 2 and 0 mm showed no difference in fixation between 7 and 9 mm screws. However, a comparison in both tibiae and femora of 7 and 9 mm screws with a gap size of 1 mm showed superior fixation with the 9 mm screw on both sides. It was recommended that 7 mm screws should not be used on the tibial side.

Interference has been defined as the amount by which the diameter of the screw exceeds the gap between the bone block and the tunnel wall. This corresponds to the screw thread engaged within bone.

The diameter of the interference screw has also been shown to influence the fixation of hamstring grafts. Tendons placed in tunnels of the same diameter and fixed by bioabsorbable interference screws of equal size had a lower strength of fixation than when fixed with screws oversized by 1 mm. This effect was not as significant as increasing the length of the screw. The diameter determined fixation mainly by a press-fit mechanism. Fixation is also influenced by the total contact area of thread which is determined by the outer diameter of the thread and the length of the screw.

Webb demonstrated that the load to failure was proportional to the size of a hamstring graft. Grafts of 7.0, 7.5 and 8.0 mm were secured by a 7 x 25 mm RCI screw. The proportion of grafts which failed by shearing decreased with increasing size of the graft. However, by overdrilling the bone tunnel to 8 mm, shear was abolished but load to failure did not significantly improve.

Different considerations may be important in the fixation of hamstring and B-PT-B grafts. Increasing the diameter of the screw increases the fixation of a hamstring by a press-fit mechanism crushing the surrounding cancellous bone. However, poor engagement of the thread into the tendon may make this less important and the length of the screw more so. Engagement of the thread into a cortico-cancellous B-PT-B block gives good fixation which is influenced by changes in the diameter of the screw and less by changes in the length.

**Insertion torque and BMD.** The insertion torque of an interference screw has been shown to be a predictor of load to failure in the fixation of both B-PT-B and hamstring grafts and is also important in fixation of hamstring grafts with spiked washers. For a given gap and screw size the mean insertion torque for a metal screw is significantly higher than for a bioabsorbable screw, but this may depend on the geometry of the thread. Although Pena et al demonstrated no correlation between the strength of fixation of B-PT-B grafts and BMD, Brand et al concluded that fixation by the interference screw was maximal at angles up to 10°, but that there was a significant

**Position of the screw.** The central placement of an interference screw between the four limbs of a hamstring graft increases the area of bone-tendon contact available for healing within the tunnel. Experiments performed in a polyurethane foam model showed no compromise in fixation with central compared with eccentric placement of the screw. In a similar study in human cadaver knees, although central placement conferred no advantage over eccentric placement regarding load to failure and slippage, it did result in superior stiffness. Central placement forms the basis of the Intrafix tibial fixation system.

**Divergence of the screw.** Angular deviation of the interference screw from the bone block may occur during insertion, particularly on the femoral side. It may be reduced by inserting the femoral screw through the same portal used to ream the femoral tunnel. A study in which the femoral tunnel and interference screw were inserted through an accessory medial portal resulted in a mean divergence of 6.9° in only 9% of cases. Schroeder, in a radiological study, showed reduced divergence of the femoral screw by introducing it through the tibial tunnel. Brodie et al reported significant divergence in only 8% of cases using the same technique.

In a radiological comparison of endoscopic reconstruction of the ACL and the traditional two-incision method, divergence of more than 5° occurred in 36% of screws inserted endoscopically, but with the two-incision technique divergence was not observed.

How much divergence of the screw can be accepted? A study of the effect on pull-out strength of changing the angle of the interference screw relative to the bone block concluded that fixation by the interference screw was maximal at angles up to 10°, but that there was a significant
Biodegradable screws are breakage and concerns over biocompatibility of crystalline polylactides, may take years to disappear. A clinical study by Alicea et al showed no correlation between divergence and measurements of laxity in 100 consecutive endoscopic B-PT-B reconstructions. The mean angle of divergence in each group was below 8°. No clinical study could be identified which correlated angles of divergence of over 20° with clinical outcome.

Cortical/cancellous bone fixation. Because cortical bone is 30 times stronger than cancellous bone, the pull-out strength of the corticocancellous screw depends almost entirely on the thickness of the local cortical bone. The length of the patellar tendon graft ranges from 90 to 105 mm, but the mean length of the graft tunnels in the two-incision reconstruction technique is 120 mm. Therefore it is usually impossible for the graft to be compressed at both the tibial and femoral cortices by the interference screws. In the two-incision technique the femoral interference screw compresses the bone plug against cortical bone but engages the tibial plug into relatively weak metaphyseal cancellous bone. In the one-incision method the tibial and femoral bone plugs are placed more distally, allowing cortical interference fixation within the tibial tunnel. The latter technique explains the superior fixation of the graft achieved by this technique. Similar observations were made in a study of hamstring fixation in calf bone. In one part of the study the outer tibial cortex was removed by overdrilling, allowing cancellous-only interference screw fixation. When corticocancellous interference fixation was achieved, there was a higher load to failure and less slippage under cyclical loading. The increased strength in the outer cortical bone shell allied to that of the subchondral plate of the tibial plateau provides the rationale for the use of long interference screws that match the length of the tunnel. Similar performance is obtained using matched pairs of short screws placed at both ends of the tibial tunnel.

Biodegradable interference screws
Biodegradable screws have been developed as an alternative to metal. The advantages include the absence of a signal artefact on post-operative MRI and a potentially easier revision procedure. The main disadvantages of biodegradable screws are breakage and concerns over biocompatibility. Differences in the degradation characteristics of different biodegradable materials may affect their performance after implantation.

Biodegradable screws should provide sufficient mechanical fixation until adequate biological fixation has been achieved and should then degrade completely. Some materials, such as polyglycolides, degrade and lose their mechanical strength in a few weeks while others such as crystalline polylactides, may take years to disappear.

When compared with their metal counterparts many biodegradable screws have performed similarly under biomechanical test conditions with both hamstring and B-PT-B grafts. However, there has been large variability in these investigations with regard to the choice of specimens, the direction of the test force applied and variations in the polymers selected. This makes direct comparisons between implants difficult.

Most standardised experiments comparing different biodegradable screws fabricated from different polymers have shown that nearly all the screws tested could withstand physiological post-operative loading. It has been demonstrated that in sheep adequate biomechanical properties persisted for 52 weeks.

Biodegradable composite materials are being developed, in which inorganic particles such as hydroxyapatite are mixed within the degradable polymer matrix. The aim is to enhance the regrowth of bone as the polymer degrades, rather than leaving a cavity. There is little clinical experience of these materials at present.

Conclusions
Reconstruction of the ACL aims to reproduce the mechanical and biological properties of the original ligament. Current choices of autograft have loads to failure which are comparable with the intact cruciate ligament but their fixation does not. The fixation of these grafts must be able to withstand early post-operative forces until graft-to-tunnel healing has occurred. The fixation should ideally be anatomical and at the site of insertion of the ligament. It should facilitate graft-tunnel healing, producing a normal histological transition zone between the host bone and the neoligament. The fixation device should offer these properties until incorporation of the graft has occurred. Resorbable devices may then degrade completely, removing any compromise to revision surgery. At the time of insertion they offer a strength of fixation similar to that of metal devices. Interference fixation of a B-PT-B graft fulfils many of these criteria but concerns about the adequacy of soft-tissue fixation of hamstring grafts persist, particularly on the tibial side. This has prompted many to continue to adopt a more conservative approach to post-operative rehabilitation.

References


