

# FUNCTIONAL ANATOMY OF THE ANTERIOR CRUCIATE LIGAMENT

## FIBRE BUNDLE ACTIONS RELATED TO LIGAMENT REPLACEMENTS AND INJURIES

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**This work studied the fibre bundle anatomy of the anterior cruciate ligament. Three functional bundles – anteromedial, intermediate, and posterolateral – were identified in cadaver knees. Their contributions to resisting anterior subluxation in flexion and extension were found by repeated tests after sequential bundle transection. Changes of length in flexion and extension and in tibial rotation were measured.**

**None of the fibres were isometric. The posterolateral bundle was stretched in extension and the anteromedial in flexion, which correlated with increased contributions to knee stability and the likelihood of partial ruptures in these positions. Tibial rotation had no significant effect.**

**The fibre length changes suggested that the ‘isometric point’ aimed at by some ligament replacements lay anterior and superior to the femoral origin of the intermediate fibre bundle, and towards the roof of the intercondylar notch.**

It has long been realised that the anterior cruciate ligament (ACL) does not function as a simple band of fibres with constant tension as the knee moves. Hey Groves (1920) reported that the ACL was made tense by extension of the knee. After an extensive cadaveric study, Brantigan and Voshell (1941) refined this description by differentiating between the actions of the anterior and posterior fibres. This was confirmed by Girgis, Marshall and Al Monajem (1975), who described the bone attachments and a reciprocal tightening and slackening of the anterior and posterior fibre groups in flexion and extension. Unfortunately, conflict persists with regard both to the anatomical and functional aspects of the ACL. A correct understanding of these matters is essential if reconstructions are to restore normal knee physiology. The purpose of this paper is to investigate further the anatomy and function of the natural ACL.

The micro-anatomy of the ACL is widely accepted

– an hierarchy of collagenous structures bundled together into fascicular units 0.25 to 3 mm in diameter (Danylchuk, Finlay and Krcek 1978) passing directly from femur to tibia or taking a spiral path around the axis of the ligament. These load-bearing elements are enveloped by synovium (Arnoczky 1983).

The literature becomes confusing when the fascicular anatomy is categorised. Welsh (1980) and Arnoczky (1983) described the ACL as being a single broad continuum of fascicles, with different portions taut throughout the range of motion. Odensten and Gillquist (1985) found no evidence of separation into bundles when examining transverse sections histologically. However, Girgis et al (1975) divided the ACL into two parts: a smaller anteromedial and a larger posterolateral band, a description which has been accepted as a basis for understanding the function of the ACL (Reiman and Jackson 1987; Arnoczky and Warren 1988). Norwood and Cross (1979) divided the ACL into three functional bundles, mapped their attachments and described their different actions in resisting rotatory instabilities.

Various authors have investigated ACL length changes with knee movement using radiography and metallic markers (Wang and Walker 1973; Trent, Walker and Wolf 1976), strain gauges attached to the ligament fibres (Arms et al 1984; Henning, Lynch and Glick 1985), an instrumented spatial linkage (Hefzy and Grood 1986), three-dimensional digitising (Sidles et al 1988; Butler 1989), and the movements of cords passed through bony

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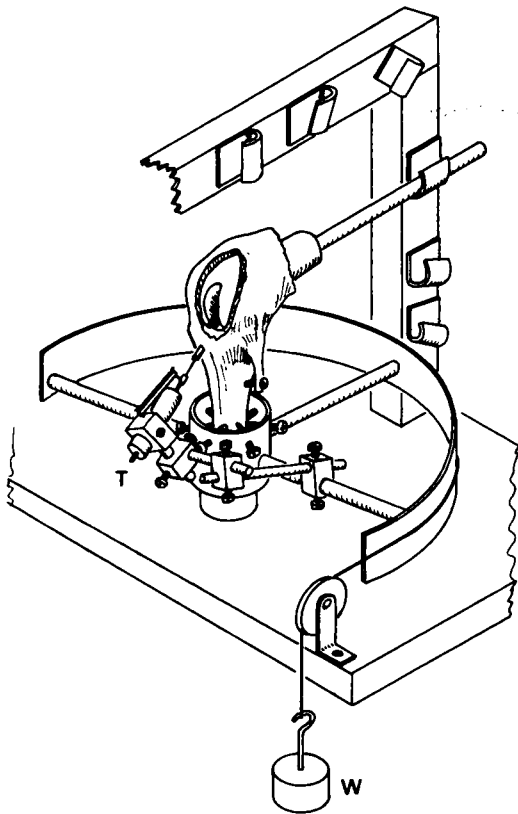


Fig. 1

Rig for the measurement of fibre length changes. The tibial mounting rotates about a vertical axis, and rotation torques can be applied by the hanging weight (W). The transducer (T) moves with the tibia, while its moving armature is attached to the fine wire that passes from the fibre origin along the ACL and through the tibia.

tunnels (Hefzy and Grood 1986). Studies of the length changes of ACL implants passed through bone tunnels measure motion which is not demonstrably normal (Hoogland and Hillen 1984; Odensten and Gillquist 1985; Graf 1987; Melhorn and Henning 1987; Penner et al 1988; Schutzer, Christen and Jakob 1989). Apart from Butler (1989), who derived fibre lengths by stepwise digitising in one specimen, no one has measured the lengths of actual ligament fibres. Straight line distances between attachments of theoretical 'pseudo fibres' (Hefzy and Grood 1986) have been reported by most authors. The work described in this paper aims to rectify this omission. It provides data on the behaviour of the normal ligament which may assist the surgeon in clinical diagnosis and techniques of reconstruction.

## MATERIAL AND METHODS

Twenty-seven cadaver knees were removed at post-mortem complete with surrounding soft tissues and 150 mm of femur and of tibia. They were sealed in polyethylene bags and stored at  $-18^{\circ}\text{C}$ . After thawing, the bone shafts were cleaned of soft tissue, leaving the collateral ligament attachments intact. The patella,

patellar ligament and quadriceps were excised, to obtain good access to the ACL, taking care not to disturb the menisci. This dissection does not significantly affect passive anteroposterior knee stability (Amis 1989). The fibula was excised distal to the neck and its head secured to the tibia by a cortical bone screw to simulate the restraining effect of the interosseous membrane.

The fibrous structure of the ACL was revealed by careful dissection of synovial tissue from its surface. Clefts were probed only with a blunt dissector until the areas of bone attachment were defined clearly. In some knees there was no easily separable interface between bundles, particularly between the intermediate and the posterolateral bundles. The medial femoral condyle was removed, providing a clear view of the ACL. After separation, the fibre bundles were held by loops of thread and transected sequentially. The areas of bone attachment were defined when the bundles were excised.

The effect of knee movements on the lengths of the fibre bundles was examined. With the knee in mid-rotation at  $90^{\circ}$  flexion, the point of a drill guide was placed at the centre of the tibial insertion of each bundle. Drill holes 2 mm in diameter were directed through the flare of the tibia, coaxial with each of the fibre bundles. A brass tube was fixed into each drill hole with its proximal end level with the tibial plateau. Lengths of 0.15 mm steel wire were folded in half and twisted together, giving double strands with a loop at one end. These loops were fixed into the centre of each bundle origin on the femur with wire staples 8 mm long and 2 mm wide. The staples were buried in the femur, leaving only the fine wires within the ligament. The wires were eased into interfascicular clefts along the fibre bundles, then through the tibial tubes to allow length changes to be measured during movement.

By means of converging pointed screws, the tibia was secured in a cylinder, which was mounted on ball bearings to allow free internal or external rotation (Fig. 1). An adjustable frame on the tibial holder held a Sangamo 10 mm stroke displacement transducer. This was positioned coaxial to a tube passing through the tibia, and the wire emerging from the tube was attached to the sliding transducer armature. The wire was kept tight by attaching a rubber band applying 1 N tension to its distal end. The transducer output, shown on a chart recorder, was calibrated against the movement of a micrometer spindle.

The femur was maintained at particular angles of flexion by clipping a long intramedullary rod into a fixed frame. This minimal restraint did not inhibit secondary tibiofemoral movements. The transducer output was monitored from  $0^{\circ}$  to  $130^{\circ}$  flexion and back to full extension, for each of the three ACL bundles with the tibia free to move into neutral rotation. A system of weights (W) hung over pulleys was then used to apply an internal or an external rotation torque of 1 Nm to the tibia (Fig. 1), and the bundle length measurements were



Fig. 2

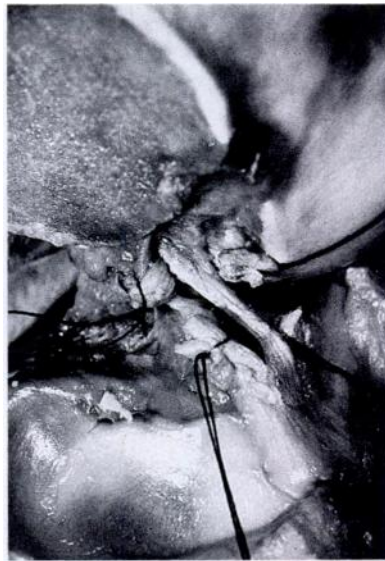


Fig. 3

Figure 2 - The intact ACL in a left knee has had the synovium removed, revealing the fibre bundles at 90° flexion. From left to right: anteromedial, intermediate, and posterolateral bundles. Figure 3 - After removal of the medial femoral condyle, the relative positions of the femoral origins are seen: the intermediate bundle is intact, with the anteromedial bundle on its left side and the posterolateral bundle on its right. The insertion of the posterolateral bundle is hidden by the intermediate bundle.



Fig. 4a

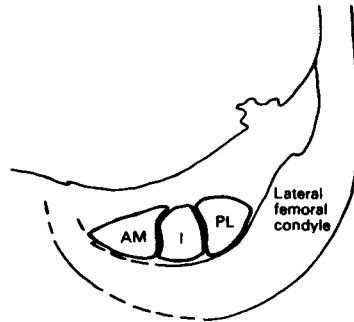


Fig. 4b

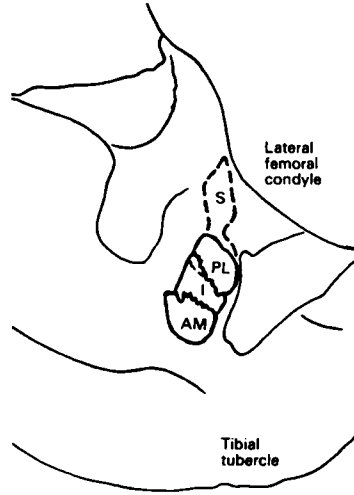


Figure 4a - Same view as in Figure 3, after excision of the ACL, showing the tripartite area of origin (AM = anteromedial, I = intermediate, PL = posterolateral). Figure 4b - Tibial plateau of the same specimen showing the tripartite ACL insertion with a synovial fold (S) posteriorly. The lateral femoral condyle is at top right, and the tibial tuberosity below.

repeated. A T-piece on the intramedullary rod prevented femoral rotation in extension.

The knees were mounted in an Instron 1122 materials-testing machine for anteroposterior stability tests. The shafts of both tibia and femur were potted in steel tubes using polymethylmethacrylate bone cement.

The tibia was fixed in mid-rotation to the load cell on the moving cross-head of the test machine. The femur was fixed to the base of the machine at either 20° or 90° flexion.

The cross-head moved at 20 mm per minute, reversing direction whenever the load reached 150 N,

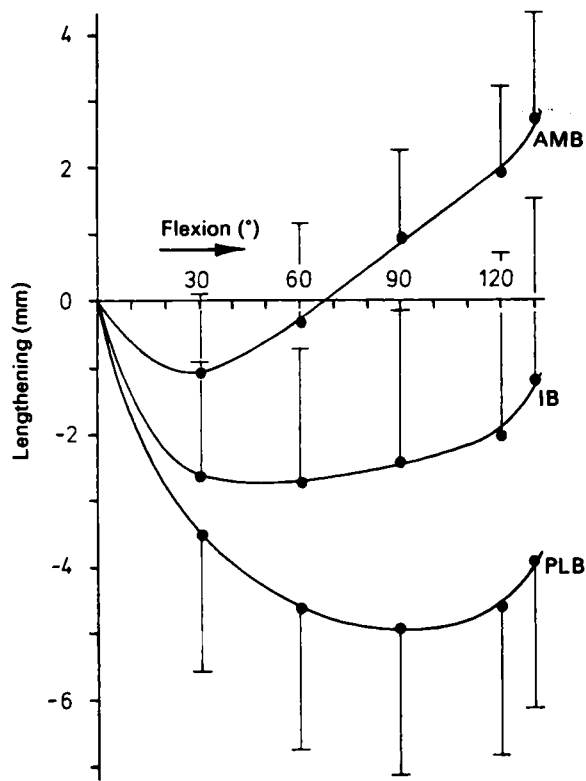


Fig. 5

Mean length change patterns for the three ACL bundles during flexion in neutral rotation (SD; n = 9). AMB = anteromedial bundle, IB = intermediate bundle and PLB = posterolateral bundle.

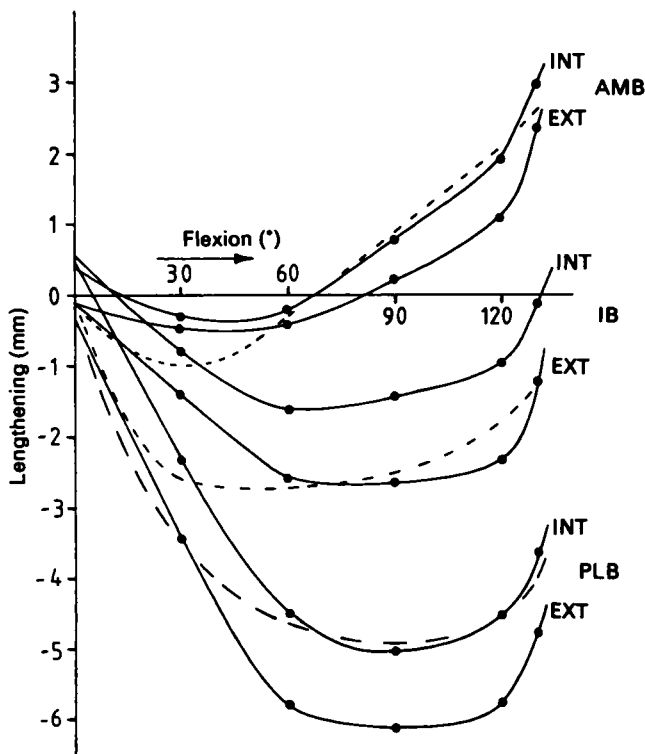


Fig. 6

Mean length change patterns for the three ACL bundles during flexion, in internal (INT) and external (EXT) tibial rotation. Torque applied to tibia = 1 Nm, interrupted lines show neutral rotation curves.

giving continuous cycles of anterior and posterior glide. A graph plotter drew curves of load against cross-head motion. It was assumed that bone deflections were negligible at the low forces used. Therefore, cross-head movement was equivalent to tibiofemoral subluxation. The intact joint was tested at 20° then 90°, after which the anteromedial, the intermediate and then the posterolateral fibre bundles were transected and the test repeated at each angle at each stage.

The contributions of individual fibre bundles were assessed at the position of maximum anterior tibial displacement with the ACL intact. As the ligament bundles were cut, the load required to reach that displacement decreased, and could be measured from the load-displacement graph. This was recorded as a percentage of total contribution of the ACL. This is 150 N minus the load resisted by the secondary restraints, measured after the ACL had been transected completely.

### RESULTS

**Anatomy.** The anatomical study confirmed the appearance of three fibre bundles in most knees when the ACL was viewed within the intercondylar notch (Norwood and Cross 1979). These are shown with the ligament intact in Figure 2, and after further dissection in Figure 3. In specimens from younger subjects the ACL was enveloped in synovium; it was sometimes difficult to separate the ligament into discrete bundles. In these cases the anterior aspect of the ACL was folded on itself in flexion suggesting an arrangement of bundles, but the probe did not slip readily into clefts. It was still possible to develop a three-bundle structure corresponding to the folding, but it was felt that the teasing apart was artefactual. In older specimens, however, the separate bundles were often obvious, with only a thin synovial covering. The areas of origin and insertion of the load-bearing fibre bundles of a typical specimen are shown in Figure 4.

**Fibre length changes.** The mean patterns of length changes for the three fibre bundles when the tibia was in neutral rotation are shown in Figure 5. All fibre bundles elongated during the final 30° of extension; none were isometric. In general the anteromedial band tightened in flexion (the positive length change indicating that the bone attachments moved apart), and the posterolateral band slackened. Tibial rotation had no significant effect on ACL fibre lengths (Fig. 6), but internal rotation tended to lengthen the fibres more than external rotation, most obviously at about 30° of flexion.

**Anteroposterior stability.** A typical set of force versus displacement curves is shown in Figure 7, for a knee at 20° flexion. It shows that the largest single bundle contribution came from the posterolateral fibres (47%), with 22% of the 150 N anterior force resisted by 'secondary restraints' after complete ACL transection. The increases in tibial subluxation allowed by sequential

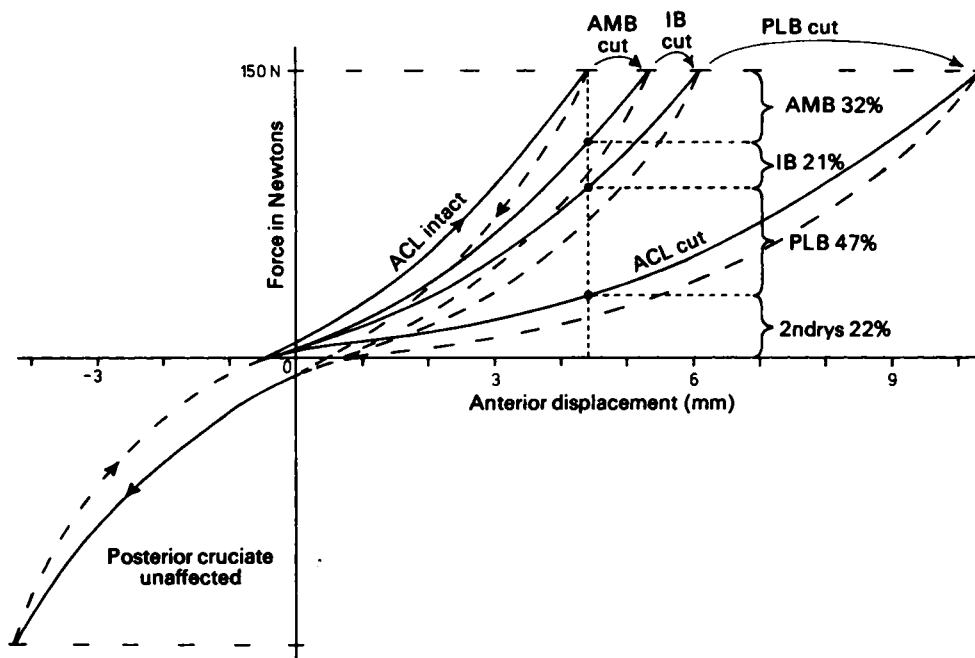


Fig. 7

Typical force versus displacement curves for a knee at 20° flexion. Sequential bundle cutting, in the order AMB, IB, PLB, allowed increases in anterior tibial subluxation before 150 N force was reached. The 'ACL CUT' curve shows a 22% contribution to anterior drawer resistance from the secondary restraints at 4.3 mm subluxation.

bundle cutting are represented across the top of the graph. The percentage contributions of the three bundles to anterior drawer resistance of the ACL at 20° and 90° flexion are shown in Figure 8, which reveals a reciprocal action between the anteromedial and posterolateral bundles.

DISCUSSION

The ACL has a complex structure and current reconstructive procedures using simple bands of tissue or artificial material can only make an approximation to this. Surgeons never see the entire ligament clearly, nor how it relates to the rest of the knee, while researchers must damage the adjacent tissues to gain such a view. Many observations therefore are based on what can be seen via an anterior arthrotomy. Even when working in vitro it is usual first to locate the bone attachments, and then to presume that the fibres pass in straight lines between them.

However, the fibres of the ligament are twisted upon themselves to a varying degree as the knee flexes due to relative rotations of the attachments. Thus the straight line presumption is not accurate and fibres need to be measured directly. This was confirmed by Hefzy and Grood (1986), when comparing changes in length, measured by intra-articular wires, with those predicted using straight lines.

One obstacle to fibre measurement has been the lack

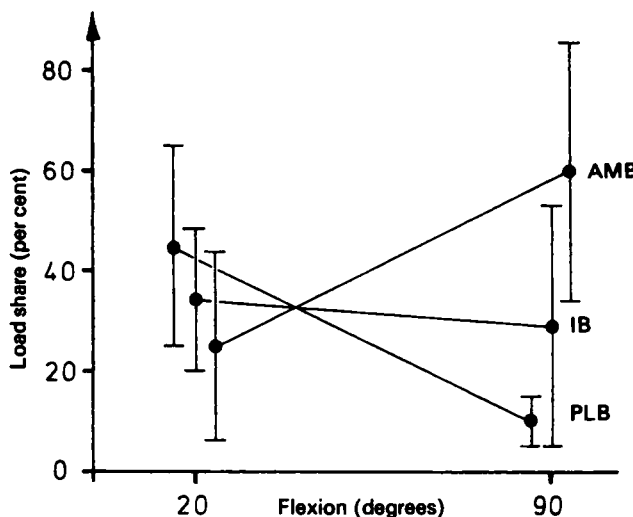


Fig. 8

The mean contributions of the three fibre bundles at 20° and 90° flexion, showing reciprocal action between the posterolateral and anteromedial bundles (mean ± 1 SD; n = 9).

of agreement regarding the structure of the ACL. The description of three fibre bundles by Norwood and Cross (1979) provided a convenient classification for localising several areas of interest within the continuum of fibres constituting the whole ligament. The present study confirmed that the ACL wrinkles into the appearance of three bundles as the knee flexes. These bundles are often demonstrably separate structures, twisted together during

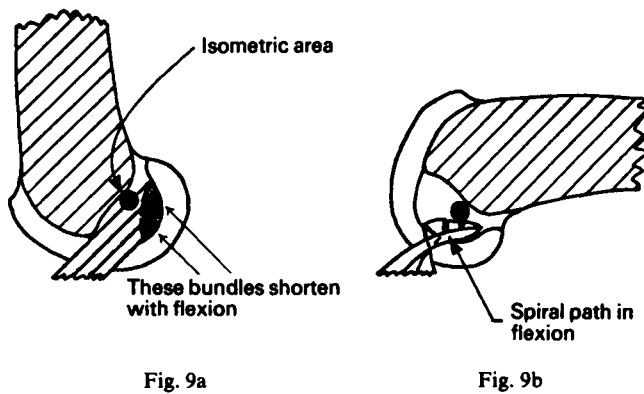


Figure 9a - The relationship of the isometric area described by Sidles et al (1988) to the fibre bundle origins within the intercondylar notch. The fibre bundle origins swing around the isometric point during flexion, thus approaching the ACL insertion. These movements cause the length changes shown in Figure 5. Figure 9b - The anteromedial bundle lengthens in flexion because it spirals around the rest of the ligament.

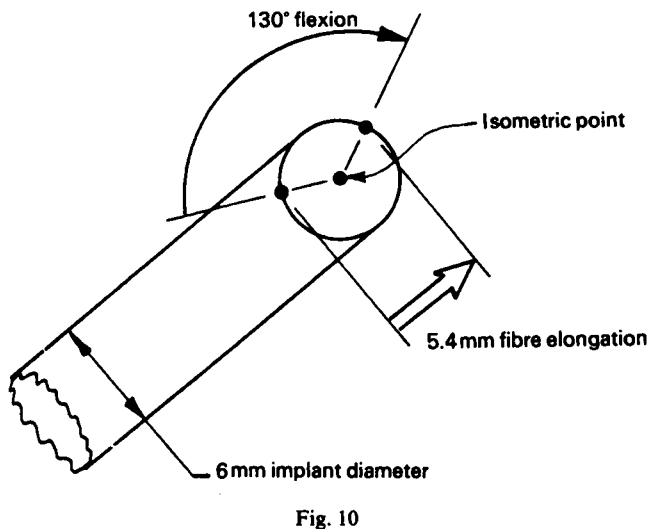


Figure 10 - Fibres in a 6 mm diameter reconstruction will have elongations up to 5.4 mm imposed on them at 130° flexion, a strain of 17% on the mean ACL length of 32 mm, even if the drill hole is centred exactly on an 'isometric' point.

flexion, but the use of the dissector to separate the fibre bundles can cross the threshold between demonstration of bundles and their creation.

The general pattern we report agrees with previous observations, that the posterior fibres slacken in flexion, leaving the anteromedial fibres to resist anterior tibial glide in the knee at 90° flexion. In search of an 'isometric point', about which the femoral origin may effectively rotate with the ligament length remaining constant, a point at the superior corner of the femoral attachment was chosen by Melhorn and Henning (1987) and Penner et al (1988), but Odensten and Gillquist (1985) chose a site at the centre of the attachment. These points

correspond to the anteromedial and the intermediate bundle attachments which we found to have mean length changes of 4 mm and 3 mm, respectively (see Fig. 5).

In the literature, confusion arises from two main sources, inaccurate work and flawed experimental method. Prior publications have reported isometric points, but then revealed large tolerances for isometricity. The drill guide method of Odensten and Gillquist (1986), for example, produced mean length changes of 3.5 mm. It is also fallacious to report 'isometric points' after taking measurements using cables through a knee which lacks its ACL, since the two cruciates are elastic and work against each other during flexion and extension. They control tibiofemoral motion, which cannot be normal if one cruciate is absent.

The most thorough study of isometricity in the intact knee (Sidles et al 1988) reported isometric points near the roof of the intercondylar notch, outside the ACL origin, and close to the junction between the anteromedial and intermediate bundle origins (Fig. 9a). This area was also defined by Graf (1987). The fibre length changes shown in Figure 5, however, can only be reconciled with this isometric point if the elongation of the anteromedial fibres is due to them wrapping around the rest of the ligament (Fig. 9b). This twisted configuration was investigated by Butler and Stouffer (1983). The anterior location of Sidles' isometric point, outside the ACL origin, explains why the intermediate bundle does not have a constant length, which might otherwise be expected from the reciprocal length patterns of the anteromedial and posterolateral bundles. The assumption of 'neutral fibres' within the ACL (Bradley et al 1988) is not justified.

However, even if the transcondylar drill hole hits an isometric point exactly, Figure 10 shows that the fibres of the reconstruction can still be stretched 17% by knee flexion. Since the natural ligaments originate from relatively large areas of bone, it is impossible for most of the fibres to be isometric; for example, those anterior to the axis must stretch during flexion (Amis 1985). These length changes have been computed for the ACL by Bradley et al (1988).

Sidles et al (1988) noted impingement of their 'pseudo fibres' against the intercondylar notch roof in extension, so real implants, probably 6 mm in diameter, would undoubtedly impinge here if fixed at Sidles' isometric point. It has been reported that 'over the top' implants tighten in extension (Penner et al 1988; Amis 1989). Since they pass close to the path of the anteromedial bundle, the opposite characteristic might be expected (see Fig. 5). These observations suggest that it is deflection by the roof of the notch which is responsible for tightening. This is supported by the finding of Melhorn and Henning (1987) that a trough 5 mm deep, which shifts the 'over the top' implant away from the roof of the notch, aids isometricity.

Since our study has not identified an isometric fibre

bundle, and considerable length changes are inevitable within a real implant, even if it is centred on an isometric point, the effect of fibre length changes is important. Cyclic loading of ligaments produces permanent stretching if the elongation exceeds 5% to 6% (Penner et al 1988). Various ACL lengths have been published (Kennedy, Weinberg and Wilson 1974, 39 mm; Girgis et al 1975, 38 mm; Trent et al 1976, 22 mm; Norwood and Cross 1979, 31 mm; Odensten and Gillquist 1985, 31 mm), giving a mean of 32 mm. An elongation of 6% is therefore only 2 mm, beyond which damage must be expected. If the ACL fibres are to stay within this limit, the length changes found in our study must start from below the resting length, that is be allowed by slack. The length changes shown in Figure 5 are relative to the arbitrary datum at full extension; a study of fibre tensions is required before their resting lengths can be known. Since the length changes shown in Figure 5 are produced solely by the kinematics of knee movement, any loading of the ACL will extend it further.

Tibial rotation torques of 1 Nm did not cause significant ACL elongation. Therefore twisting is resisted by a combination of capsular shearing, slanting collateral ligament action and joint surface and meniscal geometry, while the cruciates play only a secondary role (Noyes et al 1980; Amis 1985).

The reciprocal length patterns of the anteromedial and posterolateral bundles (Fig. 5) fit well with the changes in load sharing shown in Figure 8. This supports the report of Furman, Marshall and Girgis (1976) that transection of the anteromedial bundle caused a positive anterior drawer sign and a negative Lachman sign, while the converse was true for the posterolateral bundle. Paley et al (1986) reported similar findings, except that the anteromedial bundle was also found to affect the Lachman test. This suggests that partial ruptures can affect different bundles, depending on the posture at the time of injury. Furthermore, differential changes between the two clinical tests could allow the diagnosis of partial rupture, and prediction of the affected bundle. Unfortunately, there is such a wide range of 'normal' anterior drawer stability (Amis 1989) that it is sometimes difficult to diagnose even a complete ACL rupture, since passive knee movement may remain within the normal range. However, cutting the posterolateral bundle has a greater effect on the Lachman test than cutting the rest of the ligament (Fig. 7). The same is true for the anteromedial bundle and the anterior drawer test. Thus, if only one of these signs is positive when compared with the normal contralateral knee, a partial rupture of a predictable part of the ACL has probably occurred.

Our study has provided a pointer to the future development of artificial cruciate ligaments. At present these have a single-bundle configuration and their insertion is a compromise. Multi-bundled implant structures will provide a closer approach to normal knee behaviour (Radford and Amis 1990), with their structure

acting in a manner analogous to the fibre bundles described above. This approach has been reported by Zaricznyj (1987), who used a doubled semitendinosus tendon passing from the femur to separate tibial insertions.

## CONCLUSIONS

- 1) The multi-fascicular structure of the ACL can be described in terms of three functional fibre bundles, although these are not necessarily separate entities.
- 2) The fibre bundles were not isometric in flexion/extension, the main changes being lengthening of the anteromedial bundle and shortening of the posterolateral bundle during flexion.
- 3) The changes in fibre length correlated with their changing participation in total ACL action as the knee flexed.
- 4) The different bundle contributions to flexed and extended postures can explain and aid in the diagnosis of partial ACL ruptures.
- 5) Our observations provide design data for more sophisticated implants.

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