The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament

Part 1: Tibial attachment

Andrew Edwards¹, Anthony M. J. Bull² and Andrew A. Amis³

(1) Department of Mechanical Engineering, Imperial College London, London, SW7 2AZ, UK andrewed@doctors.org.uk

(2) Bioengineering Department, Imperial College London, a.bull@imperial.ac.uk

(3) Departments of Mechanical Engineering and Musculoskeletal Surgery, Imperial College London a.amis@imperial.ac.uk

Abstract

The tibial attachments of the individual anteromedial (AM) and posterolateral (PL) fibre bundles and the entire attachment of the anterior cruciate ligament are described, relating them to consistent bony landmarks; 55 fresh-frozen specimens were measured. The fibre bundles were separated and excised at their attachments and their peripheries marked with a pen. High-resolution scaled digital photographs were taken of each dissected specimen and transferred onto a computer for analysis. A wide variation was found when using the posterior tibial axis, the anterior tibial surface and the medial tibial spine as reference points. The most consistent measurements used the tibial interspinous “over-the-back” ridge as a datum. The attachments of the PL and AM bundles were centred 10 ± 1 mm (mean $\pm$ SD) and 17 ± 2 mm anterior to the over-the-back ridge. They were 4 ± 1 and 5 ± 1 mm, respectively, lateral to the medial tibial spine border. The positions of 6 mm circles in the posterior-medial limits of the fibre bundles (representing tunnels in a double-tunnel reconstruction) were measured. The overall dimensions of the tibial plateaux correlated significantly with many measurements. The results from this study could be used to guide ACL reconstruction techniques.

Introduction

The accurate placing of the graft tunnels is critical to success in anterior cruciate ligament (ACL) reconstruction. The tibial tunnel is usually placed in a relatively posterior location within the ACL attachment, thus avoiding femoral notch impingement and possible damage to, or rupture of, the graft when the knee extends [3,10]. Biomechanical and anatomical studies have shown that the ACL is not an isometric structure, but rather composed of two functional fibre “bundles” that have different tensions at different angles of flexion of the knee [2, 8, 16, 18, 19]. Ferretti et al. [7] have recently published a work on fetal ACL morphology describing distinct AM and PL bundles. The ACL fibres can be separated from each other into an anteromedial (AM) fibre bundle and a posterolateral (PL) fibre bundle referring to their attachment areas on the tibia (Fig. 1) by flexing and extending the knee to display their different tightening/slackening behaviour. In particular, the PL bundle becomes tight in knee flexion angles between 0° and 30° , whilst the AM bundle remains tight throughout flexion when an anterior displacement force is applied [2, 5, 19], allowing clear differentiation to be made between the two bundles. This is similar to that reported by Sakane et al. [18] who used strain gauges to

differentiate between the two bundles whilst passively flexing the knee. As ACL reconstruction surgery evolves, the use of a double-bundle technique is being explored in order to more closely imitate the natural anatomy and function, in terms of anterior laxity and tibial rotation, than that attained by single-bundle grafts. Although double-bundle reconstructions that only utilise one tibial tunnel and two femoral tunnels have been described [22, 23], it is normally accepted that an “anatomic” ACL reconstruction has two tunnels in both the tibia and femur, giving two grafts in parallel within the extended knee. Placement of the tibial tunnels will have similar constraints on them as in the single-tunnel technique for ACL reconstruction, principally trying to avoid femoral intercondylar notch impingement onto the graft [10]. In order to be able to navigate accurately to the correct graft tunnel locations, details are needed of the intra-articular ACL attachment anatomy and geometry. The authors are aware of only one study that gave quantitative data describing the locations of the tibial ACL bundle attachments [21]. Such data are needed for the design of drill guides and computer-assisted surgery software.

Fig. 1 An articulated left knee specimen with a the anteromedial and posterolateral fibre bundles isolated and tied. b After removal of the ACL and the bundle attachments outlined

The aims of this study were to provide an accurate description of the positions of the AM and PL fibre bundles and related ACL reconstruction tunnel positions using anatomical bony landmarks, and to relate the anatomical positions of the fibre bundles to the size of the knee. This first part of the work describes the tibial ACL attachment.

Materials and methods

Thirty-two disarticulated tibial plateaux and 23 articulated specimens with ACLs intact were examined. The specimens had not been fixed, but had been frozen and used in other studies. The ages of the specimens were not known in all cases, but most were between 65 and 80 years old and none had degenerative changes judged likely to affect this study.

In all specimens, the ACL was dissected by removing the synovium, sharply detaching the anterior attachment of the lateral meniscus, revealing the lateral ACL border, and removing the anterior soft tissues to reveal the anterior limit of the ACL. The attachment of the posterior horn of the lateral meniscus was intimately associated with the posterior border of the ACL, marking its posterior limit, and was sharply excised. The medial border of the ACL was confluent with the medial tibial plateau articular cartilage.

In the disarticulated specimens the ACL consistently demonstrated two fibre bundles when held in tissue forceps and tension applied proximally (i.e. perpendicular to the tibial plateau). The fibre bundles were separated proximally and the plane of separation developed bluntly to the tibial attachment. In the articulated specimens the ACL fibre bundles were identified and separated bluntly based on their fibre orientations and tensioning patterns on anterior drawer at 90° flexion and external rotations that resulted in the AM fibre bundle becoming more taut than the PL. This was confirmed by viewing the increase in tension in the PL bundle as the knee was extended from 30° to 0°. The demarcation between them was bluntly dissected to its tibial origin. The fibre bundles were then isolated with ties and cut in their midsubstance (Fig. 1a). The tibia was then separated from the femur.

In all specimens the fibre bundles were excised at their attachments and their peripheries marked with a pen, or scored with a fine osteotome, for ease of identification (Fig. 1b).

High-resolution scaled digital photographs were taken of each dissected specimen.

The anterior edge of the tibial surface was defined as the point where the tibial plateau first sloped inferiorly, consistent with a line connecting the anteriormost edges of the medial and lateral tibial condyles (point A in Fig. 2, and line A in Fig. 3). The apex of the medial tibial spine (point B in Figs. 2, 3), and the lateral border of the medial tibial spine (line C in Fig. 3) were located and marked on the specimens with a pen. The “over-the-back” ridge (point D in Fig. 2 and line D in Fig. 3) was a transverse interspinous ridge on the apex of the posterior slope of the tibial plateau, just anterior to the posterior cruciate ligament (PCL) attachment. It was located using a 2 mm diameter K-wire with a 60° bend 5 mm from its tip as a guide. This method was arrived at through a trial of different angled tips (90°, 60° and 45°) and finding the shape that best fitted the posterior slope of the tibial plateau. The interspinous “over-the-back” landmark was described by Hutchinson and Bae [11]; it is not the same as going over the back of the tibial intercondylar shelf, as in PCL reconstruction. The posterior tibial axis (E) was defined as a line connecting the posterior limits of the medial and lateral condyles. The width (F) was defined as the maximal mediolateral (ML) distance parallel to the posterior tibial axis, and the depth (G) was defined as the maximal anteroposterior (AP) distance perpendicular to the posterior tibial axis (Fig. 3).

Fig. 2 Schematic diagram and photograph of a sagittal cut through the centre of the tibia to demonstrate the positions of the landmarks used in this study (included on the photograph is the “Parson’s Knob” [4]) A anterior tibial slope, B medial tibial spine, D over-the-back ridge

Fig. 3 Schematic diagram of the tibial plateau depicting the landmarks used in this study. A anterior tibial surface, B apex of medial tibial spine, C lateral border of medial tibial spine, D “over-the-back” ridge, E posterior tibial axis, F width, G depth

Measurements were taken in an AP direction in relation to the posterior tibial axis E, the anterior tibial axis A, and the “over the back” position. Measurements were taken in the ML direction from the lateral border of the medial tibial spine, and from the medial edge of the tibial plateau, to the centres of the two ACL fibre bundles.

Further ACL bundle attachment data were obtained by using computer graphics. Best-fit ellipses were fitted into the marked ACL fibre bundle attachments; the centres of these defined the centres of the two fibre bundle attachments (Fig. 4a).

Fig. 4 Schematic diagram of a left knee depicting a the best-fit ellipses marking the centres of the AM and PL bundles, b the positions of 6 mm tunnels placed in the posteromedial limits of the AM and PL bundles, c the centre of the ACL attachment

A 6 mm diameter circle was positioned at the posteromedial limits of each fibre bundle to represent the drill holes required for double-tunnel reconstruction (Fig. 4b). The position of these circles provided space for a bone bridge between them and placed the AM tunnel in as posterior a position as possible so as to avoid possible impingement. Finally, the centre of the whole ACL attachment was found in the AP and ML directions and measurements to these points were taken from the various landmarks (Fig. 4c).

In order to relate the bundle attachments to the overall size of the tibial plateau, Pearson correlation coefficients were calculated using the tibial plateau AP depth and ML width as the independent values, with the different measurements from the various landmarks as dependent values. These correlations were taken to be statistically significant for $P < 0.05$.

Results

The tibial plateaux had a mean ML width of 80 ± 6 mm (66–90) and AP depth of 52 ± 5 mm (39–64). The transverse interspinous “over the back” ridge was a mean of 19 mm (39%) anterior to the posterior tibial axis E and 30 mm (61%) posterior from the anterior tibial axis A. A wide variation was found in ACL attachment shapes and sizes (Fig. 5). In midsubstance, the two fibre bundles were grossly of similar diameter. (Quantitative analysis of the ACL cross-section has been reported previously [9] and does not form part of this study.) The AM fibre bundle expanded considerably as it neared the tibia, so there was a relatively large AM fibre bundle attachment as compared to the PL fibre bundle attachment. The basic pattern of an AM and a PL bundle was demonstrated in 47 of 55 specimens, with 8 of 55 exhibiting a more direct anterior and posterior bundle configuration (e.g. Fig. 5, specimens 17 and 29). The AP length of the ACL attachment was 18 ± 2 mm (11–23). This correlated to the size of the tibial plateau: $r = 0.46$, $P = 0.0005$ for ML width; $r = 0.34$, $P = 0.0118$ for AP depth.

Fig. 5 A selection of ACL attachment shapes at the same scale and in the same orientation (right knee specimens have been mirror imaged to look like left knees). The scale is 1:1. The shapes are the actual sizes of the ACL tibial attachments. Note that the diagrams are aligned to the tibial posterior axis, which lead to tibial external rotation in some knees that had a small lateral plateau. This has rotated some of the attachments so that the AM bundle has moved laterally relative to the PL

Measurements to the centre of the ACL

The centre of the ACL attachment was 35 ± 5 mm (26–57) from the posterior tibial border. This was $64 \pm 5\%$ (53–74) of the maximum tibial AP depth ($r = 0.51$, $P = 0.016$). The centre of the ACL was 15 ± 2 mm (11–18) anterior from the “over-the-back” ridge ($r = 0.36$, $P = 0.091$ versus AP depth of plateau).

The ML width of the ACL attachment was 9 ± 2 mm (7–14). The centre of the ACL was 5 ± 1 mm (3–7) lateral from the medial tibial spine border, and 37 ± 4 mm (30–44) from the medial border of the tibial plateau. Both measurements had a significant correlation with the total ML width of the tibial plateau ($r = 0.8$, $P < 0.0001$).

Measurements anterior from the “over-the-back” ridge

The over-the-back ridge gave the most reproducible measurements in an anterior direction:

The centre of the PL fibre bundle was 10 ± 1 mm (8–13) and the AM fibre bundle 17 ± 2 mm (13–19). These had some correlation with the size of the plateau. In relation to the AP depth, $r = 0.64$, $P = 0.0011$ for the PL bundle; $r = 0.37$, $P = 0.087$ for the AM. In relation to the ML width, $r = 0.59$, $P = 0.0028$ for the PL bundle: $r = 0.25$, $P = 0.248$ for AM.

The PL 6 mm tunnel centre was 9 ± 0.5 mm (8–10), and the AM 6 mm tunnel was 16 ± 2 mm (12–18) anterior to the “over-the-back” ridge. These had stronger correlations with the overall dimensions of the tibial plateau (Table 1).

Measurements anterior from the posterior tibial axis

The centre of the PL fibre bundle was 28 ± 3 mm (24–35), and the AM fibre bundle, 37 ± 3 mm (31–44) from the posterior tibial axis. The PL 6 mm tunnel was 29 ± 3 mm (24–34), and the AM 6 mm

tunnel, 35 ± 4.0 mm (30–44). The distances from the posterior tibial axis to the centres of the bundle attachments correlated significantly with the ML width and the AP depth of the tibial plateaux (in relation to ML width: $r = 0.78$, $P < 0.0001$ for the PL bundle; $r = 0.89$, $P < 0.0001$ for AM. In relation to AP depth: $r = 0.84$, $P = 0.0001$ for PL bundle; $r = 0.89$, $p < 0.0001$ for AM), as did distances to the tunnel positions (Table 1).

Table 1 Pearson correlations between the AP and ML sizes of the tibial plateaux and dimensions locating the ACL attachment features

Anatomic independent value	Anatomic dependant measurement	Pearson correlation
AP tibial depth (midline)	Posterior to centre of ACL	0.51 ($P = 0.016$)
	Over-the-back to ACL centre	0.36 ($P = 0.091$)
	Length of ACL attachment	0.34 ($P = 0.0118$)
	Over-the-back to ACL posterior limit	0.22 ($P = 0.1168$)
	Over-the-back to PL bundle centre	0.64 ($P = 0.0011$)
	Over-the-back to AM bundle centre	0.37 ($P = 0.087$)
	Over-the-back to PL 6 mm tunnel	0.82 ($P < 0.0001$)
	Over-the-back to AM tunnel centre	0.60 ($P = 0.0024$)
	Posterior to ACL posterior limit	0.68 ($P < 0.0001$)
	Posterior to PL bundle centre	0.84 ($P < 0.0001$)
	Posterior to AM bundle centre	0.89 ($P < 0.0001$)
	Posterior to PL tunnel centre	0.82 ($P < 0.0001$)
	Posterior to AM tunnel centre	0.67 ($P = 0.0005$)
	Anterior to PL bundle centre	0.65 ($P = 0.0008$)
	Anterior to AM fibre bundle centre	0.43 ($P = 0.0388$)
	Anterior to PL tunnel centre	0.65 ($P = 0.0007$)
	Anterior to AM tunnel centre	0.56 ($P = 0.0052$)
	Lateral from spine to PL bundle centre	0.24 ($P = 0.2603$)
ML tibial width	Lateral from spine to AM bundle centre	0.21 ($P = 0.3208$)
	Lateral from spine to PL tunnel centre	0.19 ($P = 0.0891$)
	Lateral from spine to AM tunnel centre	0.20 ($P = 0.3677$)
	Length of ACL attachment	0.46 ($P = 0.0005$)
	Lateral to centre of ACL	0.8 ($P < 0.0001$)
	Over-the-back to ACL posterior limit	0.37 ($P = 0.0063$)
	Over-the-back to PL bundle centre	0.59 ($P = 0.0028$)
	Over-the-back to AM bundle centre	0.25 ($P = 0.2477$)
	Over-the-back to PL tunnel centre	0.55 ($P = 0.0065$)
	Over-the-back to AM tunnel centre	0.50 ($P = 0.0152$)
	Posterior tibia to ACL posterior limit	0.74 ($P < 0.0001$)
	Posterior to PL fibre bundle centre	0.78 ($P < 0.0001$)
	Posterior to AM fibre bundle centre	0.81 ($P < 0.0001$)
	Posterior to PL tunnel centre	0.74 ($P < 0.0001$)
	Posterior to AM tunnel centre	0.68 ($P = 0.0004$)
	Anterior to PL fibre bundle centre	0.59 ($P = 0.0028$)
	Anterior to AM bundle centre	0.43 ($P = 0.0429$)
	Anterior to PL tunnel centre	0.61 ($P = 0.0019$)
	Anterior to AM tunnel centre	0.55 ($P = 0.0061$)
	Lateral from spine to PL bundle centre	0.19 ($P = 0.3742$)
	Lateral to AM fibre bundle centre	0.17 ($P = 0.4322$)
	Lateral from spine to PL tunnel centre	-0.10 ($P = 0.6652$)
	Lateral to AM tunnel centre	0.08 ($P = 0.7041$)

Measurements posterior from the anterior tibial axis

The distance posteriorly from the anterior tibial surface to the centre of the PL fibre bundle was 21 ± 3 mm (13–26), and the AM fibre bundle, 12 ± 2 mm (7–17). These also correlated to the size of the tibial plateau (in relation to ML width: $r = 0.59$, $P = 0.0028$ for PL bundle; $r = 0.43$, $p = 0.0429$ for AM bundle. In relation to AP depth: $r = 0.65$, $p = 0.008$ for PL; $r = 0.43$, $p = 0.0388$ for AM).

The centre of the 6 mm PL tunnel was 21 ± 3 mm (17–24), and the 6 mm AM tunnel was 13 ± 3 mm (7–17) posterior to the anterior tibial surface.

Measurements lateral from the medial tibial spine

The distance from the lateral border of the medial tibial spine to the centre of each fibre bundle attachment was 4 ± 1 mm (3–5) for the PL fibre bundle and 5 ± 1 mm (3–8) for the AM fibre bundle. The PL 6 mm tunnel was 4 ± 1 mm (2–7) lateral to the medial tibial spine, and the AM 6 mm tunnel was 4 ± 1 mm (2–6). These small dimensions did not correlate to the sizes of the tibial plateaux (e.g. $r = 0.19$, $P = 0.374$ for PL bundle; $r = 0.17$, $P = 0.432$ for AM in relation to ML width of plateau).

Discussion

This study has found that intra-articular landmarks on the tibial plateau, the “over the back” ridge and the lateral face of the medial tibial spine, could be used as starting points from which to locate the centre of the ACL attachment, and also the attachments of the AM and PL bundles. Because these bony landmarks are very close to the ACL attachment, the distances between the landmarks and the centres of the ACL bundle attachments do not vary much, despite the range of overall knee sizes, so they are the most precise means for locating the centres of the fibre bundle attachments. Their location near the centre of the tibial plateau also means that they are easily accessible arthroscopically. This means that their use, with instruments designed to reference from them, should lead to consistently accurate placement of graft tunnels for either single- or double-bundle ACL reconstruction. An important aspect of this method is that it defines both the AP and ML positions, a fundamental principle for finding a position on a surface. This is necessary in order to avoid graft impingement on the edges of the femoral intercondylar notch.

Previous authors have described reference points to position single tibial tunnels in ACL reconstructions. The posterior tibial axis gave results similar to other studies when measuring the AP position of the centre of the ACL tibial attachment [1, 10, 20]. Howell [10] used the femoral notch roof to guide the position of the tibial tunnel, and Hutchinson and Bae [11] used an “over-the-back” position based on the anterior border of the PCL as a reference.

“Point-and-shoot” drill guides are used most frequently for the tibial graft tunnel, where the surgeon visualises the optimal position and places the point of the guide into the ACL attachment based on the arthroscopic view. These guides rely on the judgement and experience of the surgeon; an instrument that locates on a bony landmark could require less skill and be more consistent. In addition, the present authors were not aware of publications on the use of a guide to position the tunnels in a double-bundle tibial technique.

Any landmark that is used as a reference point has to be accessible, easily recognised and provide accurate, reproducible measurements. Measurements from the posterior tibial axis may be used in the future when utilising computer guidance systems, especially as there is a strong correlation between the size of the tibial plateau and the measurements referenced from here. However, it is not an accessible reference landmark arthroscopically. Although measurements from the anterior tibial surface had similar ranges and standard deviations, defining the position of the anterior tibial surface is rather subjective and it is not visible arthroscopically. Similar problems of lack of practicality affect the anterior landmarks defined by Takahashi et al. [21]. It was not possible to measure accurately in the AP direction from the medial tibial spine because the exact AP position of its summit was not identified easily; this has been reported previously [11]. However, when measuring from the interspinous “over-the-back” ridge, the measurements showed small standard deviations and ranges. Hutchinson and Bae [11] described the “over-the-back” position and the anterior border of the PCL in flexion as the most reliable and accurate reference. Colombet et al. [6] published a similar study to ours in 2006 examining the ACL attachments of seven cadaveric knees. They also found the interspinous ridge (which they call the “retro-eminence ridge”) their most useful landmark. Their depictions of the tibial attachment of the ACL showed a mediolateral arrangement of the bundles in all their specimens. However, they described the centres of the bundles according to the “parallel projection” of the central fibres of the detached bundles and this resulted in the centres of the bundles being AM and PL within the ACL attachment in a similar arrangement to the results of this study. Similarly, Morgan et al. [15] developed a method of referencing off from the PCL itself. The PCL was not considered in this study because the authors were looking for bony landmarks only and were unsure of the reliability of using a deformable structure as the reference point.

Chhabra et al. [5] recently published a work describing the importance of appreciating the double-bundle nature of the ACL. They produced arthroscopic, radiographic and cadaveric evidence of the bundles as separate anatomical structures in line with the work published by Ferretti et al. [7]. Our experience of dissecting cadaveric knees did not reveal the bundles to be two separate anatomical structures, but areas of the ACL that could be separated from each other into AM and PL fibre bundles by flexing and extending the knee to display their different tightening/slackening behaviour.

In describing how they locate their tibial tunnels in reconstruction surgery, they report using soft tissue structures including the root attachment of the lateral meniscus (to identify the PL bundle), the PCL, and visualisation of the actual tibial attachment of the ACL’s two bundles. Although the tibial attachment of the ACL is associated intimately with the meniscal attachments, we do not feel that their soft edges would provide positive locations for instruments.

The lateral positions of the bundle attachments from the medial tibial spine lateral border had weak correlations with the overall dimensions of the tibial plateaux, but these were small distances with smaller standard deviations and narrow ranges, so this does not imply lack of precision when measuring laterally from the nearby tibial spine.

The range of sizes of the specimens used in this study matched earlier publications [14, 20]. Similarly, the AP size of the ACL tibial attachment matched that reported by Odensten and Gillquist [17].

This suggests that the specimens used in this study were representative of the population. The authors are not aware of evidence to suggest that the ACL attachment varies with age, the specimens being older than ACL reconstruction patients. The advantages of working in vitro included the ability to gain better access for the measurements.

Quantitative data found in the literature (by Takahashi et al. [21]) differed from the findings in this study: they found that the overall orientation of the tibial ACL attachment was predominantly in the ML direction, so the centre of the PL bundle was reported to be only 1.7 mm posterior to the centre of the AM bundle. It appears that we have made a different interpretation of the posterior extent of the ACL as it approaches the tibia. Takahashi et al. found the bundle centres around 29 and 32% of the overall AP depth of the proximal tibia, whereas Staubli and Rauschning [20] found the overall centre of the ACL tibial attachment at 43% in their cryosections. Our results report the bundle centres at 29 and 46%, and the centre of the ACL attachment at 36% of the AP depth of the tibia.

We have presented data for the graft tunnel positions that can either be at the centres of the bundle attachments or else at their posteromedial areas. Drilling the tibial tunnel too anteriorly results in notch impingement with the knee in extension. This can result in a loss of extension or graft damage [10] and the formation of a “cyclops” lesion [13]. Ikeda et al. [12] reported that anterior placement of the tibial drill hole resulted in greater AP translation than in their comparison group where the tibial tunnel was placed more posteriorly. Although we have received anecdotal reports and observed at surgery, that grafts placed at the centres of the bundle attachments do not cause graft impingement in anatomical double bundle ACL reconstruction, we have also presented data that gives the safest graft placement against impingement while still placing the grafts in the anatomical fibre bundle attachments.

In fact, this is suggesting that the tunnels are placed only 1 mm posterior to the centres of the bundle attachments. This small difference underlines the small margin of error in this surgery.

Future developments of computer-guidance systems for surgical procedures might utilise the correlation between the tibial plateau dimensions and the positions of the ACL or its bundles from the anterior and posterior tibial axes to cross-check the intra-articular measurements.

This study aimed to find a measurement method that would lead to the most consistent placement of tibial tunnels for both single- and double-bundle arthroscopic ACL reconstruction. This should be based on reliable anatomical landmarks to avoid a wide variation in positions between knees. It was found that this could be done by measuring from the interspinous “over-the-back” ridge in an anterior direction, and from the lateral surface of the medial tibial spine in a lateral direction.

Acknowledgments

This research was kindly funded by the London Department of Postgraduate Medical and Dental Education. We acknowledge Ealing Hospital NHS trust for the knee specimens. Dr. Bull was supported by the Arthritis Research Campaign, a charity based in Chesterfield, UK. The authors are not aware of any potential conflict of interest relating to this article.

References

1. Amis AA, Beynnon B, Blankevoort L, Chambat P, Christel P, Durselen L, Friederich N, Grood E, Hertel P, Jakob R (1994) Proceedings of the ESSKA scientific workshop on reconstruction of the anterior and posterior cruciate ligaments. *Knee Surg Sports Traumatol Arthrosc* 2:124–132
2. Amis AA, Dawkins GP (1991) Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. *J Bone Joint Surg Br* 73:260–267
3. Amis AA, Jakob RP (1998) Anterior cruciate ligament graft positioning, tensioning and twisting. *Knee Surg Sports Traumatol Arthrosc* 6(Suppl 1):S2–S12
4. Berg EE (1993) Parsons' knob (tuberculum intercondylare tertium). A guide to tibial anterior cruciate ligament insertion. *Clin Orthop Relat Res* 292: 229–231
5. Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH (2006) Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. *J Bone Joint Surg Am* 88(Suppl 4):2–10
6. Colombet P, Robinson J, Christel P, Franceschi JP, Djian P, Bellier G, Sbihi A (2006) Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. *Arthroscopy* 22:984–992
7. Ferretti M, Levicoff EA, Macpherson TA, Moreland MS, Cohen M, Fu FH (2007) The fetal anterior cruciate ligament: an anatomic and histologic study. *Arthroscopy* 23:278–283
8. Friederich NF, O'Brien WR (1992) Functional anatomy of the cruciate ligaments. In: Jakob RP, Staubli HU (eds) *The knee and the cruciate ligaments*. Springer, Berlin
9. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL (1999) Quantitative analysis of human cruciate ligament insertions. *Arthroscopy* 15:741–749
10. Howell SM (1998) Principles for placing the tibial tunnel and avoiding roof impingement during reconstruction of a torn anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc* 6:S49–S55
11. Hutchinson MR, Bae TS (2001) Reproducibility of anatomic tibial landmarks for anterior cruciate ligament reconstructions. *Am J Sports Med* 29:777–780
12. Ikeda H, Muneta T, Niga S, Hoshino A, Asahina S, Yamamoto H (1999) The long-term effects of tibial drill hole position on the outcome of anterior cruciate ligament reconstruction. *Arthroscopy* 15:287–291
13. Jackson DW, Schaefer RK (1990) Cyclops syndrome: loss of extension following intra-articular anterior cruciate ligament reconstruction. *Arthroscopy* 6:171–178
14. Kurosawa H, Walker PS, Abe S, Garg A, Hunter T (1985) Geometry and motion of the knee for implant and orthotic design. *J Biomech* 18:487–499
15. Morgan CD, Kalman VR, Grawl DM (1997) The anatomic origin of the posterior cruciate ligament: where is it? Reference landmarks for PCL reconstruction. *Arthroscopy* 13:325–331
16. Muneta T, Yamamoto H, Sakai H, Ishibashi T, Furuya K (1993) Relationship between changes in length and force in in vitro reconstructed anterior cruciate ligament. *Am J Sports Med* 21:299–304
17. Odensten M, Gillquist J (1985) Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. *J Bone Joint Surg Am* 67:257–262
18. Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. *J Orthop Res* 15:285–293
19. Sapega AA, Moyer RA, Schneck C, Komalahiranya N (1990) Testing for isometry during reconstruction of the anterior cruciate ligament. Anatomical and biomechanical considerations. *J Bone Joint Surg Am* 72:259–267
20. Staubli HU, Rauschning W (1994) Tibial attachment area of the anterior cruciate ligament in the extended knee position. Anatomy and cryosections in vitro complemented by magnetic resonance arthrography in vivo. *Knee Surg Sports Traumatol Arthrosc* 2:138–146
21. Takahashi M, Doi M, Abe M, Suzuki D, Nagano A (2006) Anatomical study of the femoral and tibial insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. *Am J Sports Med* 34:787–792
22. Takeuchi R, Saito T, Mituhashi S, Suzuki E, Yamada I, Koshino T (2002) Double-bundle anatomic anterior cruciate ligament reconstruction using bone-hamstring-bone composite graft. *Arthroscopy* 18:550–555
23. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med* 30:660–666