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The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament. Part 2: Femoral attachment

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Abstract

The aim of this study was to describe the anatomical locations of the femoral attachments of the anteromedial (AM) and posterolateral (PL) bundles of the anterior cruciate ligament (ACL). Twenty-two human cadaver knees with intact ACLs were used. The femoral attachments of the two bundles were identified, marked and photographed. They were measured and described in terms of the o'clock positions parallel to the femoral long axis and parallel to the roof of the intercondylar notch. The centres of the bundles were also measured in a high–low and a superficial-deep manner referencing from the centre of the posterior femoral condyle, and with respect to their positions within a measurement grid defined in this study. The bulk of the AM bundle was attached between the 9.30 and 11.30 o'clock positions and the PL bundle between the 8.30 and 10 o'clock positions. The AM and PL bundles were consistently found in specific zones of the measurement grid. Using the posterior condyle reference method, the centre of the AM bundle was at 68 ± 7% (range 57–78) in a shallow–deep direction and 55 ± 5% (44–62) in a high–low direction. The PL bundle was found at 56 ± 8% (40–73) in a shallow–deep direction, and 62 ± 7.0% (40–70) in a high–low direction. The attachment was oriented at 37° to the femoral long axis. The results from this study could be used to guide ACL reconstruction techniques.

Introduction

As anterior cruciate ligament (ACL) reconstruction techniques evolve, an accurate quantitative description of the attachment anatomy is required in order to design instruments capable of placing graft tunnels so that their entrances are in anatomical locations, within the ACL attachments.

The ACL has, for some time, been described as consisting of two main functional bundles [10]. The anteromedial (AM) and posterolateral (PL) bundles exhibit differing length change patterns during knee flexion–extension [2, 4, 20, 24], with the AM bundle tighter in flexion and the PL bundle in extension. These length change patterns correlate with functional behaviour: fibre lengthening causes tension, so that the fibre bundles have differing importance in knee flexion and extension [2]. This can be duplicated by a double-bundle ACL reconstruction [25]. Previous studies on 'isometric' ACL reconstruction [9, 13, 29] have shown that length change patterns depend most sensitively on the femoral attachment location. Thus, it is essential for both a conventional single-bundle ACL reconstruction, as well as an 'anatomical' double-bundle ACL reconstruction, to have the correct femoral attachment points if it is to function in harmony with the natural ACL behaviour; this is always critical to successful ACL reconstruction surgery, whether using one or two graft bundles.

Anatomical reconstructions using double tunnel techniques are being developed [8, 15, 23, 26], but quantitative anatomical descriptions of the attachment anatomy of the ACL and its two bundles, using methods that can be employed clinically, are sparse. Several papers have presented data [6, 16, 22, 26], using a mix of anatomical and arthroscopic measurements on a range of numbers of specimens: the o'clock position, shallow and deep from the articular cartilage margins, vertical height below the roof of the intercondylar notch or above the tibial contact point.

In this study, anatomical terminology will be used to describe positions as seen in the extended knee, that is proximal–distal and anterior–posterior, while arthroscopic terminology will be used to describe the knee at 90° flexion, as viewed by the surgeon, that is deep–shallow and high–low.

The aim of this study was to define the anatomy of both the whole femoral attachment of the ACL and of its two fibre bundles according to clinical, arthroscopic and anatomical terminology, so that surgeons could obtain useful guidance for placing ACL graft tunnels anatomically. It was hypothesized that, because knees are geometrically similar, measurements to locate the bundle attachments could be correlated with measurements that describe the size of the knee.

Materials and methods

Twenty-two fresh-frozen cadaver knees were used. Their ages were not all known, but they were mostly between 60 and 75-years old. The medial–lateral (ML) widths across the femoral epicondyles and intercondylar notch were measured using digital callipers.

Having opened the joint and dissected off the synovium, the ACL was separated bluntly into its two bundles. The bundles were identified from their orientations and tension on anterior drawer at 90° flexion and external rotation (resulting in the AM bundle becoming more taut than the PL bundle). The bundles were tied and transected in midsubstance.

Soft tissues were removed from around the posterior limit of the femoral intercondylar notch and "o'clock" positions marked around it. These were found by fitting a circular disc that had clock markings on it into the posterior femoral notch, aligning the 3–9 o'clock axis with the epicondylar axis and the clock face perpendicular to the axis of the femur (Fig. 1). A set of discs in 2 mm increments from 10 to 30 mm diameters fitted all sizes of femur. The intact femur was clamped in a bench vice and a digital camera mounted 1 m away on a tripod. Photographs were taken in a distal–proximal direction parallel to the femoral shaft and also parallel to the roof of the femoral intercondylar notch.

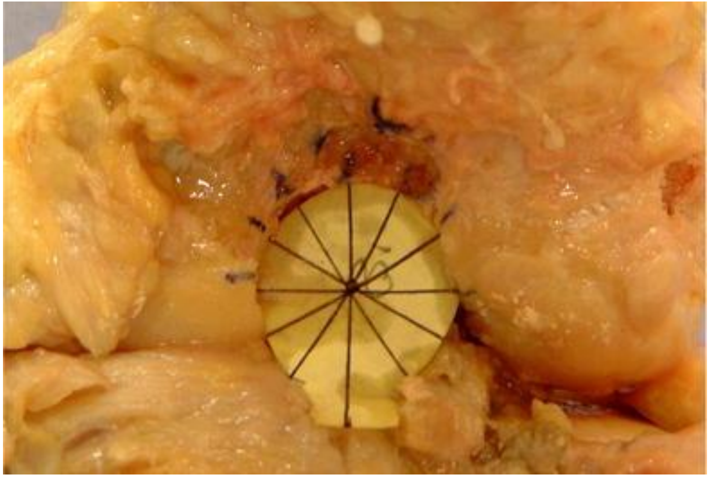

Fig. 1 Clock markings around the posterior outlet of the femoral intercondylar notch, based on a template with diameter fitting the notch and with the 9–3 o'clock axis parallel to the epicondylar axis

The distal femur was cut in the mid-sagittal plane to further examine the ACL attachment site, as described by Zavras and Amis [28]. The bundles were excised individually and the peripheries of their attachments marked in ink at the transition between ligament fibres and the adjacent periosteal or cartilage surfaces on the femur. This was estimated visually when the ACL fibres were lifted by forceps, which demonstrated clearly the end-point where they became intimate with the periosteum. Photographs of the lateral femoral condyle were taken in a true ML direction (Fig. 2).

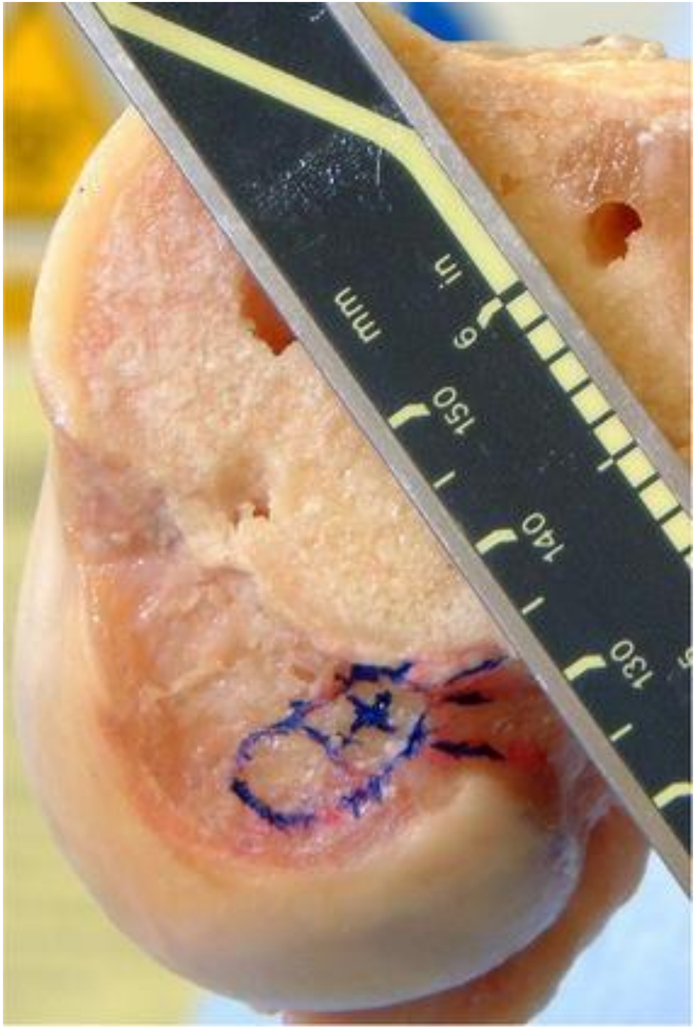

Fig. 2 The exposed lateral femoral condyle with the ACL attachment outlined in ink

Using a computer graphics program (Microsoft Word® graphics software) the ACL bundle attachments were outlined. The centres of the two bundles were located using best-fit ellipses that fitted into their attachment areas.

The positions of the ACL bundles were defined in four ways; the pre-marked o'clock positions at the posterior limit of the femoral notch were used as reference points for three. (1) Lines were drawn from the o'clock positions parallel to the femoral shaft and measurements were taken at the points where the lines intersected the ACL bundles (Fig. 3a). (2) Measurements were also taken along lines drawn from the o'clock positions parallel to the femoral notch roof (Blumensaat's line on X-ray), (Fig. 3b). Note that some of these lines were on the side of the notch, so the measurements were from the edge of the posterior condylar articular cartilage, not from the posterior outlet that is used higher in the notch. (3) A circle was fitted to the outline of the posterior lateral femoral condyle and measurements taken in "shallow–deep", and "low–high" directions according to Zavras and Amis et al. [1, 28] (Fig. 3c). (4) A measurement grid was superimposed onto the lateral view pictures with the notch roof as its superior limit and divided into 16 equal zones (Fig. 3d). This method, with its shallow, deep and lower edges matching the edges of the articular cartilage, was a surgical arthroscopic modification of a radiographic method [5].

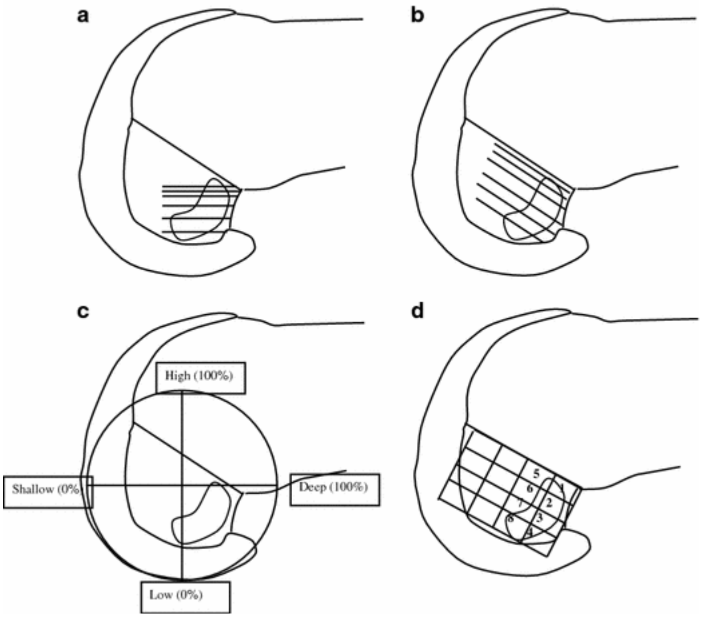

Fig. 3 a The measurement lines drawn parallel to the femoral shaft at the o'clock positions. b Measurement lines drawn parallel to the femoral notch roof from the o'clock positions. c The posterior condyle circle reference system. d The measurement grid for describing the position of the centres of the two functional ACL bundle attachments, with numbered zones

After defining the positions of the anatomical fibre bundle attachments, the computer graphics was used to position 6 mm diameter circles (that represented graft tunnels) within the ink-marked attachments. These circles were placed by judging visually the best fit within the attachments, plus also ensuring that a bone bridge was maintained between them. The positions of the centres of the 'tunnels' were then measured using the methods described above.

Further measurements were taken from the photographs: Angles between the axis of the femoral shaft and the line joining the centres of the bundles, the line between the two 6 mm tunnel centres, and the line from the 11 o'clock posterior limit to the centre of the PL tunnel. Also the distances between the two tunnels were measured in the line joining their centres, and in shallow–deep and high–low directions.

In order to check the hypothesis that measurements to locate the bundle attachments could be correlated with measurements that describe the size of the knee, correlations were examined using the Pearson correlation coefficient. The dimensions used to characterise the size of the knee were: the diameters of the femoral notch and of the posterior femoral condyle (Amis' circle), plus the AP depth and ML width of the tibial plateau. The measurements used to describe the positions of the bundle attachments included the high–low and shallow–deep positions of the femoral bundles, and the angles and distances between the bundles and the 6 mm tunnels.

Results

The epicondylar width was 81 ± 7 (67–94) mm: mean ± SD (min–max). The posterior femoral intercondylar notch had a semicircular shape with a diameter of 20 ± 3 (15–25) mm. The diameter of the posterior lateral femoral condyle was 39 ± 4 (33–47) mm. These matched sizes quoted in other studies [7, 11, 18, 27], therefore these specimens were representative of the population.

A wide variation was found in the size and shape of the ACL between specimens. The femoral ACL attachment was 14 ± 2 (8–18) mm long by 7 ± 1 (6–10) mm wide. Comparing the femoral ACL attachments to their corresponding tibial ACL attachments found no significant correlation either in length (r = 0.18, P = 0.443) or width (r = 0.04, P = 0.8730) (Fig. 4).

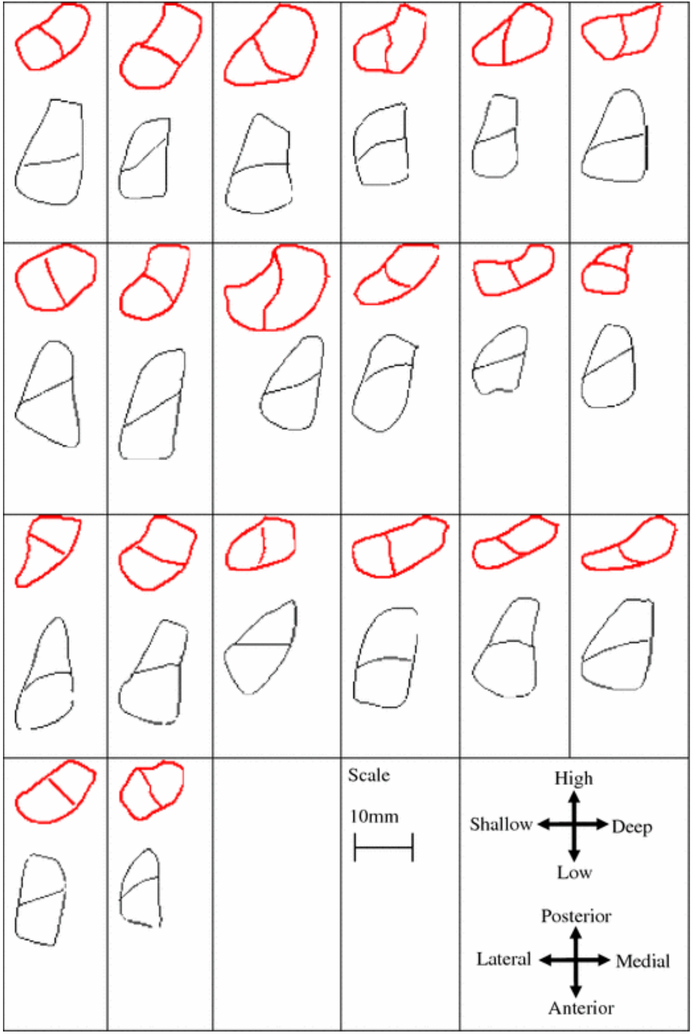

Fig. 4 ACL attachment outlines on the femur and the corresponding outlines on the tibia: femoral above tibia in each case; all shown for right knee, actual size

In all cases the AM bundle extended to the posterior–proximal limit of the femoral notch, blending with the periosteum of the femoral shaft. Both bundle attachments were of similar size and were larger in area than the cross-section of the bundles at their midsubstance. Although not quantified in this study, this difference was clearly seen visually. These findings have been reported previously by Harner et al. [12] in a quantitative analysis of the ACL.

Measurements parallel to femoral axis

The AM bundle attachment consistently reached the posterior margin of the femoral intercondylar notch between 10.30 and 11.30 positions. The bulk of the AM bundle fibres were between the 10.00 and 11.30 positions, with the greatest attachment width of 7.6 ± 1.5 mm. The centre of the AM bundle was 4.3 ± 1.1 mm from the posterior edge of the notch at the 10.30 o'clock ± 30 min position when measured as in Fig. 3a.

The PL bundle was mostly between the 09.00 and 10.30 positions, with the greatest attachment width of 6.2 ± 2.3 mm. The centre of the PL bundle was 8.9 ± 2.1 mm from the posterior edge of the notch at the 10.00 ± 18 min position.

Measurements parallel to the femoral roof (Blumensaat's line)

Using measurements as in Fig. 3b, the bulk of the AM bundle was between the 09.30 and 11.00 o'clock positions. The greatest thickness was 7.0 ± 1.6 mm. The AM bundle centre was 4.6 ± 1.2 mm from the posterior outlet at the 10.00 o'clock ±30 min position.

The bulk of the PL bundle occupied 08.30–09.30 o'clock positions. The greatest thickness was 5.5 ± 3.1 mm. The PL bundle centre was 7.3 ± 1.8 mm from the posterior outlet at the 09:00 o'clock ±18 min position.

Posterior lateral condyle diameter reference method

The diameter of the posterior condyle circle correlated significantly with the size of the knee: femoral epicondylar width (r = 0.61, P = 0.003), tibial plateau ML width (r = 0.6, P = 0.003) and AP depth (r = 0.64, P = 0.0013).

The centre of the AM bundle was correlated to the circle diameter, at 68 ± 7 (57–78) % deep (r = 0.48, P = 0.02) and 45 ± 5 (38–56) % high (r = 0.78, P < 0.001). This was at a mean position of 7.2 mm deeper and 1.8 mm lower than the centre of the circle with the knee flexed 90°.

The PL bundle was centred at 56 ± 8 (40–73) % deep (r = 0.31, P = 0.154) and 38 ± 7 (30–60) % high (r = 0.70, P < 0.001). This was at a mean position of 2.2 mm deeper and 4.9 mm lower than the centre of the circle.

Measurement grid method

The centre of the AM bundle was located primarily in zone 1 of Fig. 3d (14 in zone 1, 6 in zone 2, 2 in zone 5). The centre of the PL bundle was found primarily in zone 7 (18 in zone 7, 1 in zone 6, 1 in zone 3, 2 zone 2) (Fig. 5).

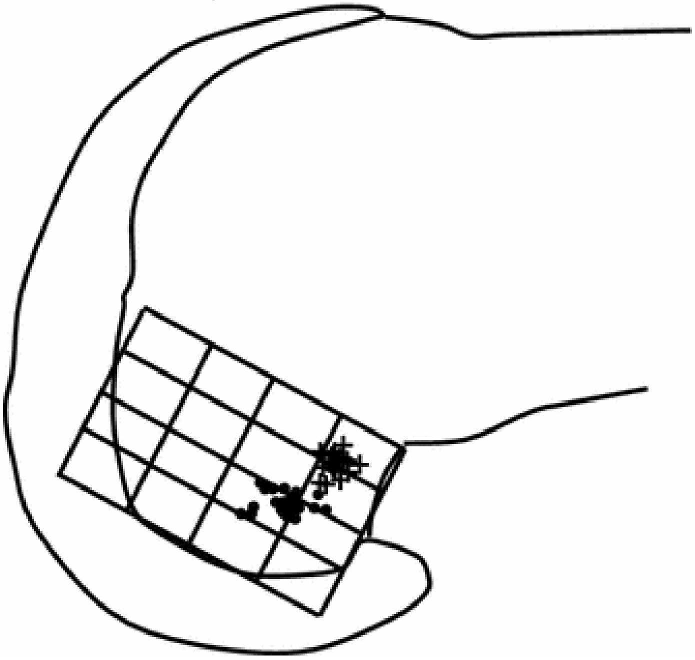

Fig. 5 The positions of the centres of the AM and PL bundles within the measurement grid

ACL axis

The line linking the centres of the two ACL bundles was at an angle of 37 ± 16 (15–70) degrees to the femoral axis, showing a large variation. The centres of the ACL bundles were 6.7 ± 1.2 mm (3.6–8.9 mm, min–max) apart.

Graft tunnel positions

The AM 6 mm tunnel was located consistently at the 11 o'clock position, close to the posterior edge of the notch, with its centre 5 mm shallow from the posterior edge of the notch in the direction parallel to the axis of the femur. The PL tunnel was in the same position as the centre of the anatomical attachment, at 10.00 o'clock and 9 ± 2 mm from the posterior outlet (Fig. 6).

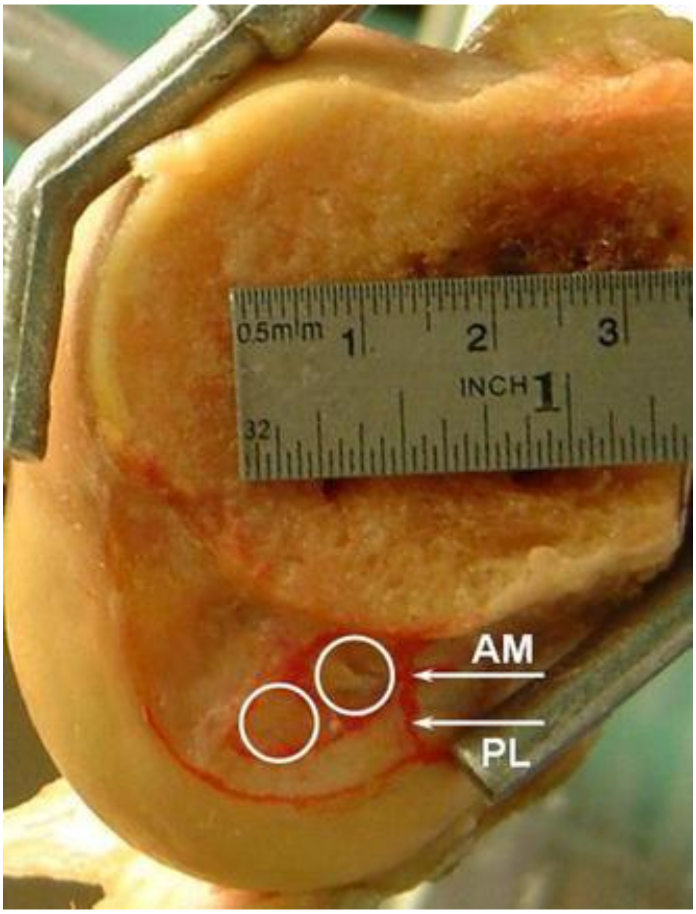

Fig. 6 Photograph and 6 mm diameter circles overlaid, representing the method used to position the graft tunnels, with the AM tunnel at 11.00 o'clock, 4.5 mm from the posterior edge and the PL tunnel at 09.40 o'clock, 10 mm from the back, when measured parallel to the axis of the femur

In relation to the AM tunnel, the PL tunnel was 8 ± 1.3 (6–12) mm away, at 36 ± 11 (23–60) deg direction from the femoral axis. This could also be described as 7 ± 1.6 (5–10) mm shallower and 5 ± 1.4 (3–7) mm lower in the notch.

These dimensions did not correlate significantly with the size of the femur: for example, distance between AM and PL bundles: $r = 0.24$, $P = 0.29$ versus epicondylar width and also versus the diameter of the posterior condylar circle. However, the small SDs (approximately ±2 mm) suggests small variation between knees.

Discussion

This paper has presented data describing the location and extent of the femoral attachment of the ACL. Several measurement systems have been used, reflecting methods published previously. Each has its own strengths and weaknesses, some being immediately useful for the surgeon, while others may be used as input data for computer-assisted navigation methods linked to surgical guidance instruments. Some of the measurement methods were modified in order to make them more relevant to arthroscopic surgery.

Accurate femoral graft tunnel placement is essential for success in ACL reconstruction [3]. Sommer [21] found a significant correlation between the femoral single bundle placement and the International Knee Documentation Committee (IKDC) score. As the placement of the graft as seen on X-ray moved away from the most isometric point, the IKDC scores decreased. It will be just as critical to achieve optimum graft placement in the double bundle technique as it is in the single bundle technique. Therefore knowledge of femoral ACL attachment anatomy is critical to the success of both single and double-tunnel reconstructions.

Anatomic reconstruction of the ACL, replacing both the AM and PL bundles, is a technique that is gaining in popularity and is supported by laboratory evidence. Radford and Amis [19] reported that a double-bundle reconstruction controlled anterior laxity better than single-bundle reconstructions, across the range of knee flexion. Yagi et al. [25] reported finding the biomechanical outcome, especially in rotatory loading, may be superior with double bundle reconstructions compared to single bundle reconstructions, and Mae et al. [15] similarly found better antero-posterior stability using a two femoral socket technique when compared to the standard single socket ACL reconstruction. Mommersteeg et al. [17] described the complexity of the fibre architecture of the ACL and suggested that successful ACL reconstruction may not be achieved simply by replacing one bundle.

Noting the increasing interest in double-bundle 'anatomic' ACL reconstruction, an accurate map of the attachments of the ACL fibre bundles on the femur will be important both in the development of double bundle techniques and in outcome studies to describe optimal and suboptimal positions for graft placement. An accurate description of the attachment locations of the AM and PL bundles of the ACL will aid development of new guides and navigation software for the correct placement of graft tunnels for ACL reconstruction.

This study has described a number of measurement techniques that can be used to navigate to the centres of the femoral fibre bundle attachments of the ACL, in order to obtain the most information. The methods used have been described in previous papers, but the measurement grid technique was modified from the radiographic technique of Bernard et al. [5] into a form that could be used arthroscopically. The circle based on the posterior femoral condyle can be used for accurate navigation, in relation to shallow–deep and high–low coordinates. Amis et al. [1] reported this method in 1994, and Klos et al. [14] modified it for use with lateral radiographs. In this study this method yielded small standard deviations for bundle positions (approximately 2–3 mm) that, particularly in the high–low direction, correlated with the posterior condyle diameter. Thus, it can be used as a normalising dimension to allow for different knee sizes. It may be possible to use this finding in conjunction with standardised shallow–deep distances to individualise positions for the tunnels in double-bundle reconstructions. One potential weakness of this study was the use of older specimens than typical ACL patients. However, we are not aware of any observations that have suggested that the sizes of the ACL attachments alter with aging.

If more than one measurement technique is used it is possible to obtain more information and to cross check positions. This principle suggests that a computerised navigation system could synthesize the data in this paper in order to optimise guidance in each specific knee. For example, although the raw data is not presented, we found that measuring parallel to the femur gave more information for the AM bundle and less for the PL bundle, whilst the opposite was true for measurements parallel to the femoral notch roof. Therefore using more than one measurement technique yields the most information. The positions of the bundle attachments were measured in relation to the posterior outlet of the femoral intercondylar notch because it is close to circular there. This method is inherently more accurate than attempting to define "o'clock positions" from the anterior outlet of the notch, because (a) the anterior notch is not circular, leading to uncertainty in defining the o'clock positions, (b) the ACL is towards the back of the notch, so inaccuracy will be introduced by extrapolating measurements a longer distance than from the posterior outlet, (c) the posterior outlet is the site where the surgeon often places the hook of the drill guide, and so is the place where the o'clock position is estimated.

The measurement grid method was an attempt to simplify the description of the centres of the bundles of the ACL into arthroscopically recognisable zones. The grid used here was different to the so-called “quadrant” (which is actually a word describing a quarter-circle) described by Bernard et al. [5] in order to provide a grid that related to articular cartilage boundary landmarks that can be found arthroscopically, rather than to the overall bone geometry that can only be used radiographically. A further important point is that, by using different viewpoints to define the o’clock positions (parallel to the shaft of the femur and parallel to the notch roof), we have shown that different apparent o’clock positions are seen. This shows the importance of careful control of both knee flexion and the line of sight when trying to locate or define graft positions at surgery. We also hypothesise that, if a computer navigation system could combine all these methods together to produce an average position for the tunnels, that this might lead to greater consistency of tunnel placement, in the same manner that TKR surgery can take account of different trans-epicondylar, condylar or intercondylar notch axes to inform the choice of femoral component rotation.

Several studies from Japan have provided some similar information to that in this paper. Mochizuki et al. [16] described the centre of the AM bundle as being at 01.40 o’clock and the PL at 03.10 o’clock, when viewed parallel to the roof of the notch. At these positions, they were 6 and 9 mm, or 28 and 60%, respectively in the shallow direction in comparison to the shallow–deep distance across the wall of the notch at that height, between the articular cartilage margins. Takahashi et al. [22] used measurements similar to the grid in this study, with the AM and PL bundles at 25 and 23% shallow from the posterior cartilage margin, and 4 and 11 mm respectively below the roof of the notch. They also described the positions radiographically, in the same way as Bernard et al. [5]. Yasuda et al. [26] placed the AM bundle 5–6 mm shallow to the edge of the cartilage at the 10.30 o’clock position, and the PL bundle 5–8 mm higher than the edge of the cartilage at the point where it was lowest, at the tibio-femoral contact point. They noted that the line joining the bundles was inclined 30° posteriorly from the femoral axis. This study found that the 6 mm graft tunnels fitted best into the bundle attachments at 11.00 o’clock, 5 mm from the posterior outlet for the AM, and at 10.00 o’clock and 9 mm from the back for the PL graft. Other clinical reports have described the tunnels as AM: 7 mm, PL: 5 mm diameter [6] and both at 4.5 mm diameter [26]. These differences might affect the judgement of optimum tunnel position.

Although some of the information reported in this study would be difficult to apply arthroscopically, the aim was to present geometrical data that could be used as a basis for designing instruments or computer-guidance systems that would place graft tunnels accurately and reliably in the anatomical ACL bundle attachments, and also to evaluate accuracy of tunnel positions in X-ray studies. By doing this reliably, it is hoped that the outcomes of this more complex method of ACL reconstruction will be improved.

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