INSTRUCTIONAL REVIEW: KNEE

The anatomy of the anterior cruciate ligament and its relevance to the technique of reconstruction

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Anterior cruciate ligament (ACL) reconstruction is commonly performed and has been for many years. Despite this, the technical details related to ACL anatomy, such as tunnel placement, are still a topic for debate. In this paper, we introduce the flat ribbon concept of the anatomy of the ACL, and its relevance to clinical practice.

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For more than 30 years, the anatomical features of the anterior cruciate ligament (ACL) and its bony attachments have been investigated and the findings have resulted in modifications in the techniques of reconstruction following rupture.[1] For example, when the trans-tibial femoral tunnel drilling technique was the primary technique, a tunnel drilled on, the so-called "resident's ridge"[2] was believed to be malpositioned. It has subsequently become an important landmark for anatomical reconstruction.[3-7] With regard to the soft-tissue arrangement of the ACL, the concept of the ligament tissue being arranged in two bundles (anteromedial and posterolateral) has been demonstrated in literature,[8-11] and hence double-bundle reconstruction techniques were developed. These techniques are less commonly practiced now as some of its proponents reported problems with their use and have moved to the so-called 'anatomical' technique, which employs a femoral tunnel placed in the centre of the soft-tissue 'footprint' of the native ACL. The justification for this change is that a central tunnel between the two bundles seems logical.[10,12-14] This is comparable with the double-bundle technique on biomechanical grounds, but is simpler and more reliable. However there are reports of increased graft re-rupture rates when using the anatomical technique.[10,12-14]

Recently, a different concept of the pattern of insertion of the ACL on the femur and tibia and a flat, 'ribbon-like' shape to the ligament is gaining popularity (Fig. 1).[1,2] this may explain the problems relating to the techniques of reconstruction of the ACL used hitherto, potentially offering some advantages. This paper presents a review of the available literature concerning, and our anatomical work demonstrating, this concept.

Femoral insertion

The femoral footprint of the insertion of the ACL is crescent shaped. Its anterior border is formed by the lateral intercondylar ridge (resident's ridge). The posterior articular margin of the lateral femoral condyle forms its posterior border.[1,5,14] In our anatomical study, 111 human fresh-frozen cadaver knees were dissected and it was confirmed that the femoral insertion of the ACL was in continuity with the posterior femoral cortex (Fig. 2).[3]

Two types of insertion of the fibres of the ACL at their femoral attachment were described by Iwahashi et al[5] a 'direct type' with characteristic zonal architecture, allowing for the gradual dissipation of forces, and an 'indirect type' in which the ligament is inserted into bone by collagen fibres without a transitional zone. We also noted a direct type of insertion where fibres entered the bone almost at a right angle (Fig. 3), and microsopic examination revealed a double tidemark. This may be interpreted as a site within the ACL 'footprint' through which most force passes, or where 'micro-injuries' might arise.[15] This is supported by a number of other studies.[16,17] We would suggest, therefore, that the femoral tunnel for ACL reconstruction should be placed here, i.e. deep (proximal) and high (anterior) in the intercondylar notch within the region of the anteromedial bundle of the femoral footprint of the ACL. The fibres comprising the remainder of the femoral footprint (i.e. the 'indirect fibres') have a weaker attachment and take less of a load. They represent a 'fanning out' of tissue away from the more important direct insertion of fibres.

We recorded that the mean width of ACL, 2 mm from its femoral insertion was 16 mm (12.7 to 18.1) and its mean thickness was 3.54 mm (2 to 4.8).[3]

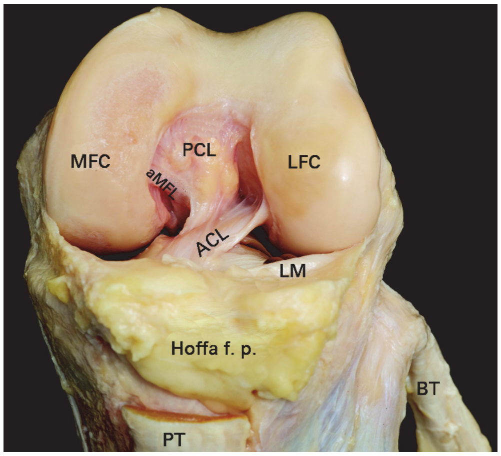

Fig. 1

Cadaver specimen showing the left knee joint. Notice the flat, ribbon-like appearance of the anterior cruciate ligament. MFC, medial femoral condyle; LFC, lateral femoral condyle; ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; LM, lateral meniscus; Hoffa f.p, Hoffa fat pad; BT, biceps tendon; PT, patellar tendon; aMFL, anterior menisco-femoral ligament (Humphrey ligament).

Fig. 2a

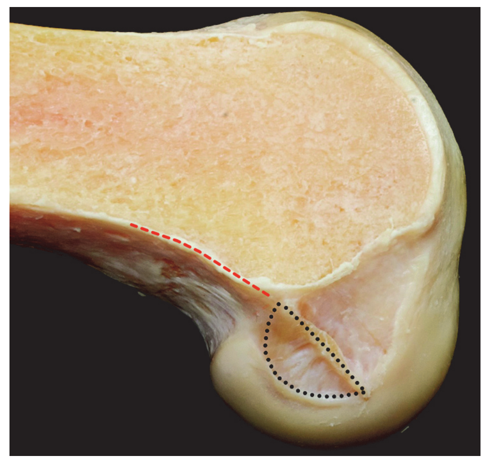

Fig. 2b

Cadaver specimens showing a) the left knee joint, lateral femoral condyle viewed from medial side. Femoral anterior cruciate ligament (ACL) attachment is visualised; b) black dots - crescent shape of ACL femoral attachment extended from the intercondylar ridge (resident's ridge) to the posterior articular margin of the lateral femoral condyle; red dashed line, posterior femoral cortex.

Mid-substance and the twisting nature of ACL

Many authors have found that the mid-portion of the ACL is either flat (Fig. 4),[3,12] or divided into two,[18] three[19,20] or several bundles. Arnoczky[21] stated that it is made of many collagen bundles, giving rise to its multifascicular nature. This historical paper also introduced the concept that the ACL has a flat, ribbon-like appearance. About 30 years ago, Odensten and Gillquist[22] dissected 33 cadaver knees and found neither macroscopic nor microscopic evidence of subdivisions of the ACL. On transverse section of the mid-portion of the ACL, they found uniform composition of the ligament with no evidence of separate bundles. Arnoczky[21] also stated that the arrangement of fibres results in a different portion of the ligament being taut, and therefore functional, at different points throughout the range of movement of the knee. This may imply functional bundles rather than separate anatomical bundles. More recently, Mochizuki et al[1] described the ACL as being made up of two bundles and recorded that "the configuration of the natural ACL mid-substance is not oval, but rather flat".

According to Amis and Jacob[23] the ACL has a twisted appearance when the ligament is viewed from the front with the knee flexed, as at arthroscopy. This twist is unwound as the knee extends. They suggested that twisting the graft at operation might be beneficial. In our opinion, this might potentially decrease the requirement for a notchplasty and its associated problems.[24] Mochizuki et al[1] also noticed that the ACL is twisted because the orientation of the tibial attachment is different from that of the femoral attachment. Odensten and Gillquist[22] had considered this more than 30 years ago, finding that with the knee flexed to 90°, the ACL is twisted by about 90°. From these observations, and our own, we concluded that the apparent appearance of the two bundles macroscopically might result from the twisted, flat ribbon-like structure of the ACL, i.e. it is an illusion. Which could explain previous observations described by different reasearchers.

Tibial insertion

The tibial insertion of the ACL has been described by many as oval in shape, being wider posteriorly, and situated anteriorly in the intercondylar area.[25-28]

Applying the 'double-bundle' theory, the anteromedial bundle is situated in the anteromedial aspect of the tibial insertion, where its medial border is the anteromedial margin of the articular surface of the medial tibial condyle.[29] The posterolateral bundle is believed to be localised in the

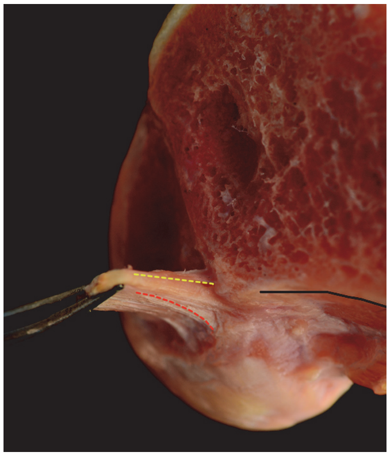

Fig. 3

Cadaver specimen of the right knee, the medial femoral condyle is cut off and lateral femoral condyle is viewed from posteromedial side. A close view of femoral attachment of the anterior cruciate ligament (ACL) to the lateral femoral condyle. The ACL is cut off about 1.5 cm from its insertion; yellow dashed line, direct ACL insertion, in a line with posterior femoral cortex (black line); red dashed line, indirect ACL insertion.

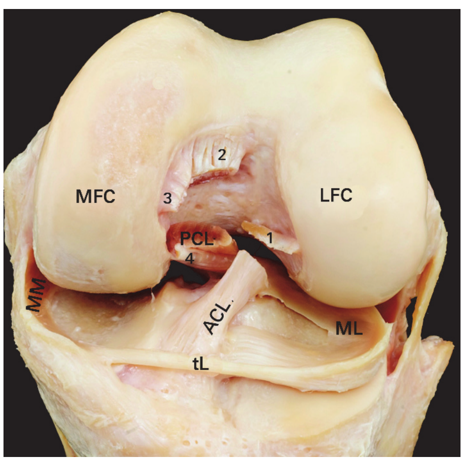

Fig. 4

Cadaver specimen of the left knee joint, frontal view, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) and anterior menisco-femoral ligament (aMFL) is cut off. Notice flat structure on the cross section of the ACL (1), and PCL (2) and aMFL (3).

posterolateral aspect of the intercondylar area, with its lateral border being the medial margin of the articular surface of the lateral tibial condyle.[29]

We first described the appearance of the ACL as 'ribbon-like' at a meeting of the ACL Study Group in 2012. This was later published by Siebold et al.[12] In this paper, the tibial attachment of the ACL was confirmed as being C-shaped (Fig. 5) from along the lateral edge of the medial tibial spine to the anterior aspect of the anterior root of the lateral meniscus, accommodating within its concavity the insertion of the lateral meniscus. Its mean width (the length of the "C") was found to be 12.6 mm (7.7 to 16.3) and its mean thickness, 3.3 mm (2.5 to 3.9). No fibres were inserted centrally, and none attached in the area ascribed by proponents of a double-bundle nature of the ACL as the attachment of the posterolateral bundle. Moreover, there were three different variants of tibial insertion. In our study (unpublished data, presented during ISAKOS Meeting in Lyon, 2015)[30] among 111 specimens 74 (67%) had a classical C-shaped insertion, 27 (24%) were J-shaped and ten (9%) were Cc-shaped (Fig. 6).

Relevance to ACL reconstruction

Restoration of the exact anatomy, unique for each patient, can be obtained in many ways, with many different grafts. Whilst bone-patellar tendon-bone and quadriceps tendon grafts are flat, perhaps hamstring grafts in the future can be positioned to mimic the ribbon-like ACL. Nevertheless tunnel placement is critical.

In the early 1990s, transtibial drilling of the femoral tunnel in ACL reconstruction was a popular method. This often resulted in a femoral tunnel that was outside the native ACL footprint, and thus truly non-anatomical. This was combined with a relatively posteriorly placed tibial tunnel, which avoided graft notch impingement, but left a rather vertical, and less effective, orientation of the graft.

The move to a central position for the tunnel in the ACL footprint followed a period of popularity of double-bundle techniques. Biomechanical studies of femoral tunnels placed centrally in the femoral footprint seemed to show better control of axial rotation of the knee than grafts placed outside the femoral footprint.[31,32] It was proposed, therefore, that the central position of the femoral graft would provide more normal kinematics and reduce the incidence of late meniscal and chondral damage and hence decrease the incidence of osteoarthritis.[33,34] Two clinical studies have evaluated this by comparing ACL grafts placed outside the femoral footprint with a centrally placed graft and have found less chondral and meniscal damage postoperatively in those placed in the centre of the femoral footprint.[35,36]

From these publications it would be natural to assume superiority of the 'anatomical' central position of the femoral footprint compared with other positions of the tunnel, but it is likely that the other positions would be suboptimal when the anatomy of the ACL which is presented here is considered.

The central femoral tunnel position was also made popular as it allows a more anterior position of the tibial tunnel, which avoids impingement of the graft against the intercondylar notch roof, while providing a graft with good obliquity in the sagittal and coronal planes, which might improve the control of axial rotation. The anatomical model presented here neatly allows a reduced risk of impingement. The twist in the ACL means that impingement is avoided.

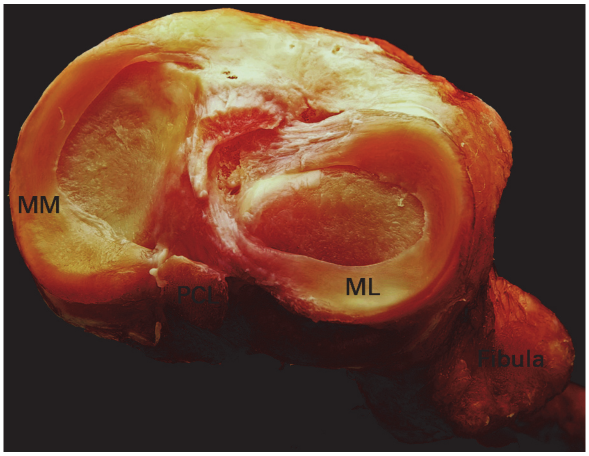

Fig. 5a

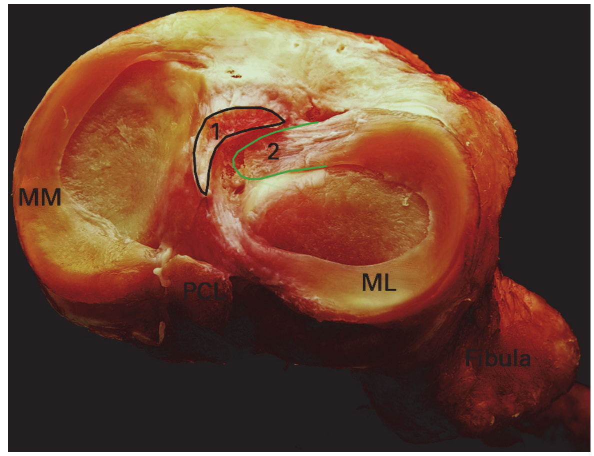

Fig. 5b

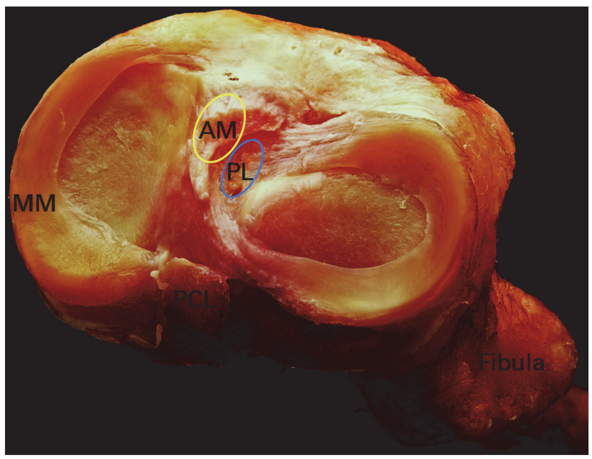

Fig. 5c

Cadaver specimens of a) the right knee joint, the femur is removed. ML, lateral meniscus; MM, medial meniscus; PCL, posterior cruciate ligament. b) 1 – C-shaped tibial attachment of the anterior cruciate ligament (ACL) (black line). 2- anterior root of lateral meniscus (green line). Note the anterior horn of the ML is surrounded by C-shaped attachment of anterior cruciate ligament. c) schematic drawing of the average description of localisation of anteromedial (AM) (yellow line) and posterolateral (PL) (blue line) bundle of the ACL and its relationship to C-shaped tibial ACL attachment. Notice that what was believed to be the position of PL attachment area is localised mostly within anterior root attachment of lateral meniscus.

In using the central position of the femoral footprint the ACL graft is less isometric than one placed in the position of the 'direct' ACL fibres. In the former position, it is common to find a negative Lachman but a grade 1 anterior drawer at the completion of the procedure.[37]

Some 40 years ago, Artmann and Wirth[38] identified a region for placement of the tunnel in the femur that provided an isometric graft. The most isometric region of the femoral footprint has been consistently localised eccentrically within the femoral footprint of the ACL in a relatively narrow band that is proximal (deep) and anterior along the lateral intercondylar ridge within the footprint.[2] This region corresponds to the 'direct' fibre insertion within the femoral footprint.

Some authors have shown that a femoral tunnel in the centre of the femoral footprint is less isometric than one placed in a more anterior region of the footprint.[38,39] Indeed, the anterior position (high in the footprint) identified by Hefzy, Grood and Noyes[40] demonstrates minor anisometry with a change of length between 1 mm and 4 mm through the range of movement. In contrast, a central femoral tunnel would be expected to demonstrate a change of length between 5 mm and 7mm, while a lower graft, in the posterolateral region of the footprint, demonstrates a change of length of about 1 cm through the range of movement.[41] As such, central grafts, or those placed in the posterolateral portion of the femoral footprint would be expected to have high tension or forces as the knee is flexed, or lose tension completely if the graft is fixed at full extension.[37] These two theoretically undesirable effects from non-isometric graft placement are supported by experimental and clinical studies that have shown non-isometric placement of the femoral tunnel can cause recurrent ante-

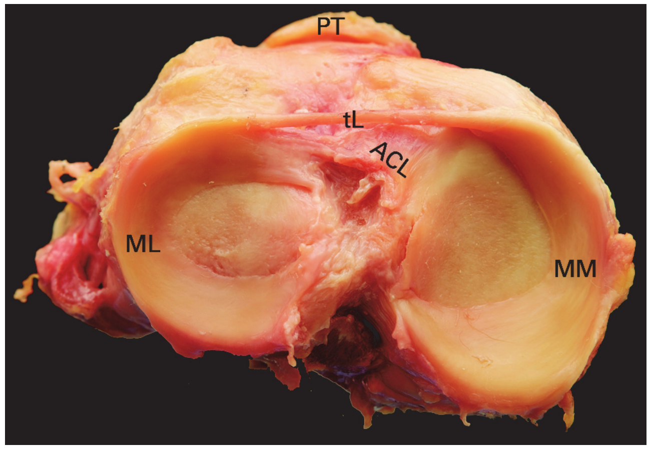

Fig. 6

Cadaver specimen of the left knee joint, the femur is removed. ML, lateral meniscus; MM, medial meniscus; ACL, anterior cruciate ligament; Tl, transverse ligament; PT, patellar tendon. Note the 'Cc' shaped tibial ACL attachment.

Table I. Rates of ACL graft re-rupture according to femoral tunnel position and graft type

	Quadrupled hamstrings (n, %)	**Mid 1/3 patellar tendon (n, %)**
Overall rate of re-rupture	14/ 125 (*11*)	7/ 81 (*8.6*)
Anteromedial position	5/ 72 (*6.9*)	1/ 22 (*4.5*)
Central 'anatomical' position	9/ 53 (*17*)	6/ 59 (*10.2*)

rior laxity.[41,42] It seems clear that isometry of the graft is important.

Markolf et al[43] showed that ACL graft fibres placed posteriorly (low) in the footprint cause high forces in the graft in extension and in some cases rupture of the graft. The importance of reconstructing the posterior region of the footprint in order to control stability at the time of the operation has to be questioned accordingly.[44]

Furthermore in recent studies,[16,17] it seems that most of the load taken by the ACL at its femoral insertion is undertaken by the 'direct' fibres' of the femoral footprint. This fits well with the anatomical model which we present here, and thus, an eccentrically placed graft is certainly no less 'anatomical' than a central position of the bundle, and is more physiological according to our concept.

There is little published work on the effect of positioning of the femoral tunnel related to risk of failure of an ACL graft. Two studies have evaluated CL graft failure with a transtibial or transportal approach and neither showed a difference.[35,45] However, the Danish Registry[46] has shown a higher rate of failure for patients undergoing an 'anatomical' reconstruction in which the anteromedial portal is used for identification and drilling a tunnel in the central femoral footprint of the ACL. In 9239 patients followed for four years, the rate of revision for anteromedial portal drilling was 5.2% compared with 3.2 % when trans-tibial drilling was performed. A recent study by Clatworthy et al[47] also shows a higher failure rate associated with anteromedial portal drilling of the femoral tunnel. The ACL grafts placed centrally in the footprint had a 3.5 times higher rate of revision than did the grafts placed in a high anteromedial position. In another study, summarised along with the findings of Clatworthy et al[48] in the same article, one of the present authors (AW) reported a rise in failure rates of ACL grafts (both hamstring and patellar tendon) in professional footballers when changing from an anteromedial bundle to the central position in the footprint for the placement of the femoral tunnel. Professional footballers are an interesting group to study. They are hard to lose to follow-up, such is their profile, and data are available on the internet for those who subsequently move clubs. As a result, for coarse data such as the rate of re-rupture of the graft, a 100% follow-up is to be expected. In addition, they will test their grafts and any flaw will be clearly evident. In less demanding groups of patients, it is harder to compare operative techniques with regard to their effect on outcome as these patients do not 'stress' their surgery as much as athletes will.

A minimum two-year follow-up of all consecutive isolated autograft ACL reconstructions in professional footballers over 12 years is presented below. Obviously, with time, more re-ruptures will occur in those with surviving grafts at the time of follow-up, but in professional football, re-rupture almost exclusively occurs within 12 months of surgery. In this case series, the mid-third patellar tendon graft is compared with the quadrupled semitendinosis/gracilis graft, and the central femoral footprint position with that in the original anteromedial position. The position of the tibial tunnel was constant throughout, entering the joint in the centre of the tibial footprint of the ACL. The results are summarised in Table I.

These findings are stark. The overall rate of re-rupture of a quadrupled hamstring graft is higher than that for patellar tendon grafts (11% *versus* 8.6%) regardless of the position of the femoral tunnel. The difference made by the choice of the position of the femoral tunnel is still more dramatic: the rate of re-rupture of a patellar tendon graft a little more than doubles from 4.5% to 10.2% in the 'anatomical' central footprint group. But there is an even larger rise in the rate of re-rupture if the hamstring grafts are considered, with approximately 2.5 times more in the central femoral footprint position (17%) compared with 6.9% in the anteromedial position.

A general defence of the central position of the tunnel in the femoral footprint by those of its proponents who acknowledge an increased rate of re-rupture is to suggest that this occurs due to better placement of the femoral tunnel causing the graft to 'work properly' and thus be stressed and have more risk of failure. In their view this is the price of better long-term outlook. They presume central femoral footprint tunnel placment will lead to better knee kinematics and hence, less risk of osteoarthritis.

Indeed, cadaveric studies have investigated the relationship between the positioning of the femoral tunnel and stability at the time of the operation, often showing better immediate control of stability, particularly in regards to pivoting type manoeuvres, when the femoral tunnel was placed more centrally in the footprint compared with a tunnel placed outside the footprint.[49-53]

However, there is emerging literature showing no significant difference in the initial post-operative stability between a femoral tunnel eccentrically placed in the footprint in the region of insertion of the 'direct fibres' when compared with a centrally placed graft.[41,54] Therefore, using a position of the femoral tunnel that is still within the femoral footprint, and thus 'anatomical' in the position of the 'direct' ACL fibres, would be expected to confer the benefits of an anatomically based position of the graft and improved isometry with lower rates of re-rupture when compared with a central or posterolateral graft, as well as better knee kinematics.

Further long-term clinical studies are clearly required to determine whether this is the case.

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R. Śmigielski: Chief investigator.
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M. Drwięga: Investigator.
B. Ciszek: Investigator.
A. Williams: Writing the paper.

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