

Biomechanics of Double Bundle Anterior Cruciate Ligament Reconstruction

by

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Thesis Abstract

The scope of this thesis was to verify whether anatomic reconstruction of the anterior cruciate ligament (ACL) with close replication of its two main bundles ensures better knee kinematics and improved clinical outcomes.

The thesis articulates into three parts. In the first part the current anatomic knowledge is reviewed with regard to the double bundle ACL structure and an anatomic study is presented: its results will serve as a basis for the following kinematics and clinical studies.

In the second part, a method to investigate cadaveric knee laxities is presented and employed to test intact and ACL deficient knees and to explore the function of the anteromedial and posterolateral ACL bundles. The ACL was found to be a primary restraint to anterior tibial translation mainly because of the action of the anteromedial bundle, with the posterolateral acting as a secondary restraint. Both bundles then were found to equally contribute to control the limit of internal rotation. Finally the reconstruction of both ACL bundles was demonstrated to be superior to traditional single bundle reconstruction in restoring intact knee anterior and rotational laxity.

The third part focused on double bundle surgical technique with the development of surgical instruments that were validated on cadaver knees and found to be extremely accurate on the tibial side, less on the femur. Surgical technique was then improved and introduced into clinical practice. Two clinical studies were conducted and demonstrated the superiority of double bundle anatomic reconstruction in improving subjective and objective results as well as instrumented knee laxity measurements.

In conclusion the main finding of this thesis was that, after a deep understanding of ACL anatomy and biomechanics, the replication at surgery of its native structure improves knee stability and patients' satisfaction.

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Chapter 1 – Introduction

1.1 Field of Study

The anterior cruciate ligament (ACL) is a primary stabiliser of the knee joint. It is the primary restraint to anterior tibial translation, helps to control rotations and avoids the pivot shift phenomenon.

The ACL is the most frequently injured ligament of the knee and accounts for approximately 50% of ligament injuries during sports activities. The natural history of untreated ACL injuries includes recurrent knee instability, inability to perform sports activities and early osteoarthritis.

ACL reconstruction has become one of the most frequent orthopaedic operations because of the increasing number of people of all ages with a desire to be active in sports, the increased accuracy of diagnosis of an ACL lesion, and the improvements in techniques and results of ACL reconstruction.

Traditional ACL surgery reconstructs the ligament with an intra-articular graft passed into the knee joint along the direction of the most isometric native ligament fibres and secured to the tibia and the femur through bony tunnels. Despite high ACL reconstruction success rates many clinical studies have reported residual subjective and objective instability, inferior activity level when compared to pre-injury and osteoarthritis progression in up to one fifth of the patients. Furthermore recent in vivo and in vitro investigations have demonstrated the inefficacy of conventional ACL surgery to restore intact knee kinematics. As the native ACL consists of two functional units, or bundles - one taut exclusively in extension and the other taut at all degrees of knee flexion - some authors have attributed these relatively unsatisfactory results to the surgical replication of only

the most isometric part of the native ACL. Hence the interest in double bundle “anatomic” ACL reconstruction has arisen.

In order to assess the efficacy and the usefulness of double bundle (DB) ACL reconstruction it is wise to test it in the laboratory prior to introduce it in the clinical practice. Several preliminary works on DB reconstruction have been performed in the past both at an experimental and clinical level. None of these studies were performed by the same Institution at a laboratory and clinical level. Furthermore most of the previous pioneer investigations suffered from lack of knowledge of key biomechanical or anatomical principles.

1.2 Outline and Scope of Thesis

In order to address the points above a cohesive set of anatomical, biomechanical, surgical and clinical studies have been conducted as part of this thesis.

In Chapter 2 the anatomical knowledge is reviewed and a new study conducted on the anatomy of the bony attachments of the ACL, in order to use the new information for laboratory and clinical works.

In Chapters 3 and 4 the contribution of the entire ACL, and of the separate bundles, to knee kinematics is investigated. Furthermore a testing methodology to explore the function of knee ligaments is described, developed and validated.

In Chapter 5 DB ACL reconstruction is performed in vitro with different techniques and compared to conventional SB reconstruction.

Chapter 6 starts the surgical technique studies. A review of the surgical principles and of the current surgical reconstructive techniques is performed. Then in Chapter 7 a commercial surgical instrument currently used for conventional ACL reconstruction is validated with respect to the new anatomic details found and presented in Chapter 2 and in Chapter 8 a new surgical instrument specifically designed for DB ACL reconstruction is described and validated.

All the new anatomic, biomechanical and surgical studies constitute the basic science for the clinical studies which are presented in Chapters 9 and 10.

In Chapter 11 the results of the thesis are summarised and discussed with reference to ongoing projects and future directions.

Chapter 2 - Anatomy of the Anterior Cruciate Ligament

In this chapter, the current literature on the anatomy of the ACL, with specific reference to the fibre bundles is analysed, and a new anatomical study is presented.

2.1 Gross Anatomy

The anterior cruciate ligament is an approximately 40mm long and 10mm wide (Girgis, Marshall, Monajem 1975) fibrous band which connects the intercondylar portion of the proximal tibia to the intercondylar portion of the distal femur. It was first described almost 2,000 years ago by Galen, a Greek physician, as a supporting structure of the knee joint rather than part of the nervous system with some contractile properties as it was believed until then (Snook 1983).

Exposure of the ACL is obtained after dissection of the most anterior knee structures including the skin, the subcutaneous tissue, the extensor mechanism, the fat pad and the synovial sheath. With the flexed knee the ACL can be visualised as a cord-like structure extending from the centre of the tibial plateau to the medial aspect of the lateral femoral condyle (i.e. the lateral wall of the intercondylar notch).

The ACL is covered by a synovial layer that is rich in blood vessels originating mainly from the middle geniculate artery. Blood vessels are accompanied by nerve fibres originating from the tibial nerve and reaching the ACL after

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penetrating the posterior knee capsule (Arnoczky, 1983). While the majority of the fibres are vasomotor, some of them lie alone among the fascicles of the ligament and may have some proprioceptive function (Arnoczky, 1983; Georgoulis, Pappa, Moebius et al 2001; Lee, Min, Choi et al 2009).

After dissecting the overlying synovial sheath the ligamentous tendon-like multifascicular appearance of the ACL becomes evident (Fig 2.1).

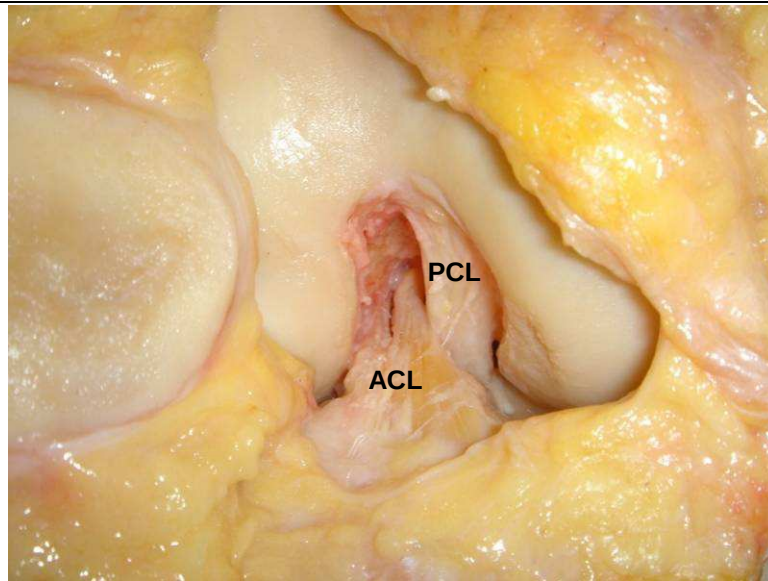


Figure 2.1: ACL exposed in a human right knee after dissection of the anterior structures

Collagen I is the main constituent of the ACL. At an ultrastructural level the individual collagen fibres have a periodic wave-like parallel configuration (Rovere, Adair 1983; Danylchuck, Finlay, Krcek 1978). Collagen fibres are arranged in a regular fascicular pattern with interfascicular spaces for vascular components (Kennedy, Hawkins, Willis et al, 1976). Each fascicle is made up of units of interlacing collagen fibrils, 150-250 nm in diameter, grouped into fibres, 1-20µm in diameter. The subfascicular units are surrounded by a loose band of connective tissue, the endotenon. Between 3 and 20 of these subfascicles are bound together, forming a fasciculus, which varies from 250µm to several millimetres in diameter and surrounded by an epitenon (Rovere, Adair 1983).

The ACL is attached to femur and tibia via collagen fibres which interdigitate with those of the adjacent bone (Cooper, Misol 1970). At the bone-ligament interface there is a transitional zone of fibrocartilage and mineralised fibrocartilage. This

allows for a gradual change in stiffness from the flexible ligament to the rigid bone, and distributes the stresses away from the attachment site.

On the tibia the ACL is attached to a wide depressed area in front of, and lateral to, the anterior tibial spine (medial intercondylar tubercle) with some variable fibres attached to the base, just medial to the attachment of the anterior horn of the lateral meniscus and fibres of the ACL may mingle with it. The tibial attachment is wider than the femoral attachment (Girgis, Marshall, Monajem 1975; Harner, Baek, Vogrin et al 1999).

2.2 Multi-bundle Structure of the Anterior Cruciate Ligament

The ACL is attached to the femur and the tibia, not as a singular cord, but rather as a collection of individual fascicles that fan out over a broad flattened area (Arnoczky 1983; Girgis, Marshall, Monajem 1975).

Due to the orientation of its bony attachments, the ligament turns on itself in a slight outward (lateral) spiral as it courses across the joint. When the knee is in the extended position the anterior cruciate is flat (Fig. 2.2). When the knee is flexed the ACL becomes wound and twisted on itself.

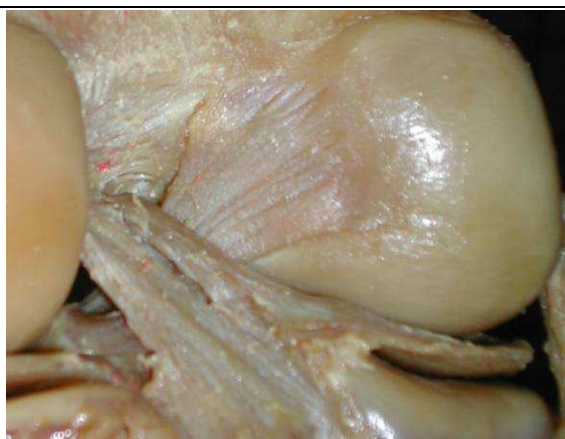


Figure 2.2: Flat ACL appearance in extension in a right knee visualised from posterior/medial

Girgis in 1975 was the first author to describe ACL functional anatomy with respect to its main bundles. In 19 cadaver knees he found that while in extension the whole ligament was taut, in deep flexion only a small anterior part was in tension and the bulk of the ligament was loose. The term anteromedial bundle (AMB) was introduced to describe the most isometric part of the ligament, which during passive flexion and extension does not change its length significantly.

In 1979 Norwood and Cross studied ACL anatomy and function in 18 freshly amputated knees. They isolated and distinguished the bundles on a purely anatomical basis and in some knees they found synovium to divide the bundles. Three main bundles were identified and distinguished upon their tibial attachment in AMB, intermediate and posterolateral bundle (PLB). The tibial attachment was described as a triangle with a posterior apex (PLB insertion) and two anterior corners (AMB and intermediate bundle). On the femur the AMB insertion was described posterior and superior in the notch while the PLB was anterior and inferior; the intermediate bundle had an intermediate position between the previous two. Selective cutting of the bundles was performed to investigate the bundles' influence on knee stability. The AMB and intermediate bundles were described as primary restraints to anteroposterior translation while when the PLB was selectively cut the tibial external rotation and recurvatum test increased.

Other investigators (Amis, Dawkins 1991; Arnoczky 1983; Butler, Guan, Kay et al 1992; Dodds, Arnoczky 1994; Fuss 1991; Harner, Baek, Vogrin et al 1999, Mommersteeg, Kooloos, Blankevoort et al 1995; Odensten, Gillquist 1985) have subsequently studied ACL anatomy and a different number of bundles has been described from an anatomic point of view, ranging from one to six. A synovial separation between bundles cannot always be identified. Age-dependent changes have been described with a real inter-bundle cleavage being more easily observed in older specimens (Amis, Dawkins 1991).

Despite the above mentioned variability and difficulties a great consensus nowadays exists that ACL complexity should be considered from a functional rather than from an anatomical point of view as a continuum of fascicles which are differently recruited through the range of motion even if two main components can be distinguished on the basis of their differential behaviour: AMB and PLB.

Amis and Dawkins (1991) measured with a transducer the changes in length of the AMB and PLB in flexion-extension and with tibial rotation. Neither of these was found to be isometric: the PLB was taut in extension and the AMB in flexion. Tibial internal or external rotation had no significant effect on bundle length.

Similarly Kurosawa, Yamakoshi, Yasuda et al (1991) employed four elongation transducers to measure the length changes in the anterior and posterior portions of the ACL. Two transducers were positioned in the anterolateral and anteromedial portions of the ligament and two in the posterolateral and posteromedial. The anteromedial and anterolateral fibres as well as the posteromedial and the posterolateral fibres showed the same elongation behaviour. Close to extension the anterior fibres were shorter and the posterior lengthened while at higher degrees of flexion the posterior became shorter and the anterior fibres lengthened.

Bach, Hull and Patterson(1997) implanted a strain gauge in the AMB and PLB and measured the strain changes during range of motion. The AMB exhibited a quasi-isometric behaviour from 10°- 90°knee joint flexion with changes of less than 1%. At full extension and full flexion the AMB stretched. The PLB on the contrary was relaxed from 40°flexion onward while in extension it elongated by more than 12% of its initial length.

The differential lengthening behaviour of the two bundles in vivo has been addressed only by Li, DeFrate, Sun et al (2004) who employed a computed reconstruction of a fluoroscopic movie obtained during a lunge activity in 5 young volunteers. The AMB showed a quasi-isometric behaviour with no statistical differences in length between different flexion angles. The PLB on the contrary was significantly longer in extension.

Sakane, Fox, Woo et al (1997) employed robotics to measure the bundles' in situ forces in response to applied anterior tibial loads ranging from 22-110 N. While the AMB was found to have a relatively constant in situ force, not changing with flexion angle, the PLB showed larger in situ force between 0-45°knee flexion with a peak at 15°.

With a similar robotic device Gabriel, Wong, Woo et al (2004) analysed the bundles' in situ forces in two loading conditions: 134 N anterior tibial load at different knee flexion angles and a combined rotatory load of 10 Nm valgus and 5 Nm internal tibial torque at 15 and 30° flexion. Under isolated anterior tibial load the PLB showed a greater in situ force towards extension while the AMB in situ force increased with flexion reaching a peak at 60° flexion. Under the combined rotatory load the PLB had a larger in situ force at 15 than at 30°. The AMB showed similar magnitudes of in situ force at both angles and were higher in magnitude than the PLB. Neither of the bundles alone could reproduce the in situ force of the whole intact ACL.

Based on the above mentioned studies evidence exists that the native ACL has an architecture that cannot be simply described from an anatomic point of view but consists of variedly orientated bundles which are recruited differently during knee motion and which can be roughly summarised as consisting of the AMB and the PLB.

2.3 Anatomy of the ACL Attachments

ACL attachment anatomy knowledge is critical for the orthopaedic surgeon who wants to perform a successful ligament reconstruction. The femoral attachment site has a greater effect on graft length changes, as the knee flexes and extends, than the tibial attachment (Hefzy, Grood, Noyes 1989; Muneta, Yamamoto, Sakai et al 1993). On the tibial side, the surgeon must pay attention to avoid an anterior graft positioning, which will lead to graft impingement with the roof of the notch during knee extension (Howell, Taylor 1993). On the femoral side, minimal displacements along the line of the roof of the notch are particularly significant (Hefzy, Grood, Noyes 1989; Zavras, Race, Bull et al 2001). These technical considerations will be discussed in Chapter 6.

Furthermore the surgeon needs to master both classic gross anatomy and arthroscopic anatomy that are slightly different, particularly in nomenclature.

2.3.1 Anatomy of the Femoral ACL Attachment

The ACL is attached on the femur to the posterior part of the medial surface of the lateral femoral condyle. This attachment is in the form of a segment of a circle with its anterior side almost straight and the posterior side convex and in an oblique direction from the vertical. It covers an area of 113 mm² on average (Harner, Baek, Vogrin et al 1999). The proximal pole is on the wall just below the “over the top position” which is defined as the superior-lateral angle of the intercondylar roof, at the junction with the lateral wall. From the proximal pole the ACL attachment spreads distally and posteriorly along the articular cartilage border for less than 20mm with a width inferior to 10mm (Fig. 2.3).

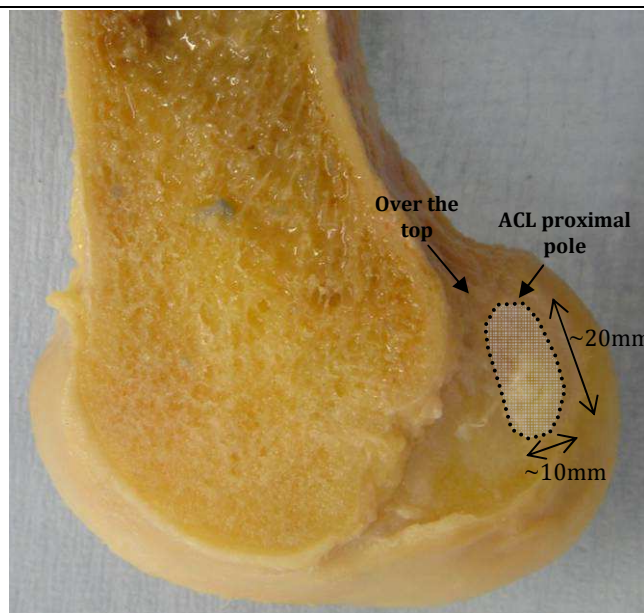


Figure2.3: Right knee ACL femoral attachment after removing the medial femoral condyle

2.3.2 Arthroscopic Anatomy of the Femoral ACL Attachment

At the time of reconstruction, mainly in chronic injuries, it is difficult to identify the ACL remnants on the lateral wall of the intercondylar notch. Moreover, using a 30° angle arthroscope, the picture of the notch changes significantly depending

on the arthroscopic portals employed. The anterolateral approach allows a frontal representation of the femoral intercondylar notch and the surgeon can easily locate the femoral attachment using the o'clock position referencing the notch as the dial of a clock. In the right knee, the femoral ACL attachment spreads from about 8.00 o'clock to 11.00 o'clock (Fig. 2.4).

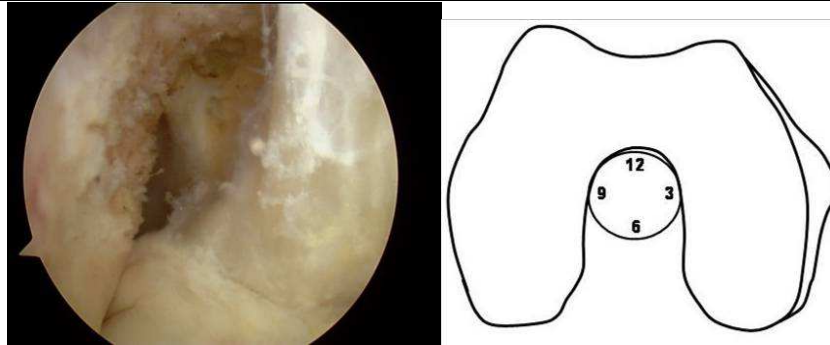


Figure 2.4: anterolateral portal arthroscopic visualization of the lateral wall of the notch and clock representation for a right knee

The antero-lateral approach on the contrary does not provide any information about the location of the ACL attachment along the wall of the notch. An antero-medial approach is needed to define the depth of the notch and to correctly see the femoral attachment to the deepest portion of the wall (Fig. 2.5).



Figure 2.5: anteromedial portal arthroscopic visualization of the lateral wall

The nomenclature at arthroscopy is different. The anatomical nomenclature refers to the knee in an extended position and the femoral ACL attachment is described using anterior/posterior and proximal/distal positions. Conversely, the arthroscopic nomenclature maps the femoral attachment referring to its position along the wall of the notch keeping the knee in flexion, so shallow/deep and

superior/inferior descriptions have been introduced to avoid confusion (Fig. 2.6) (Amis, Beynnon, Blankevoort et al 1994).

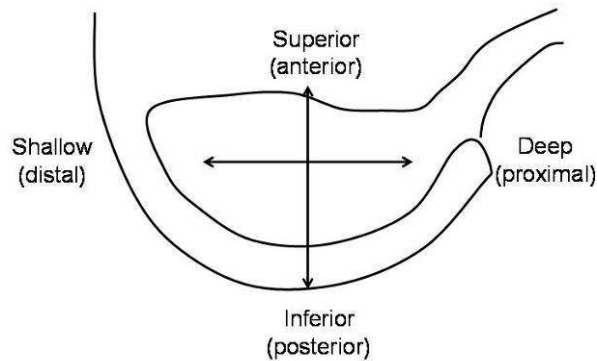


Figure 2.6: arthroscopic anatomy nomenclature to navigate the intercondylar notch

2.3.3 Anatomy of AMB and PLB Attachments on the Femur

To identify from an anatomic point of view the attachments of the AMB and PLB it is necessary to distinguish them initially from a functional point of view. If an anterior force is applied to the tibia (anterior drawer) with the knee at 90° of flexion the AMB will be taut while the PLB remains loose (Fig. 2.7)

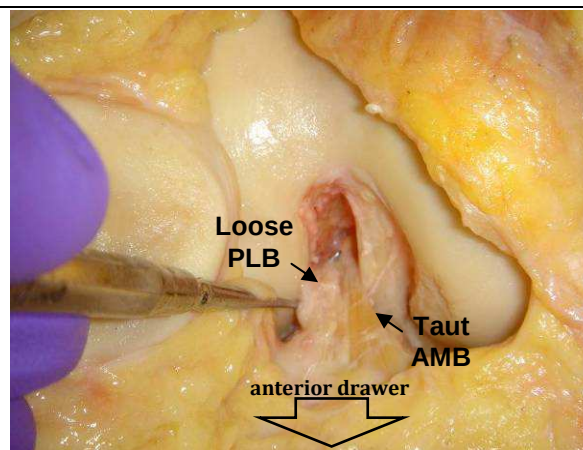


Figure 2.7: under an anterior drawer force the 2 functional bundles of the ACL are distinguishable for their different tension

In the above described loading condition the two bundles can be separated by blunt dissection (Fig. 2.8) and their attachment to bone can be identified and marked (Edwards, Bull, Amis 2007).

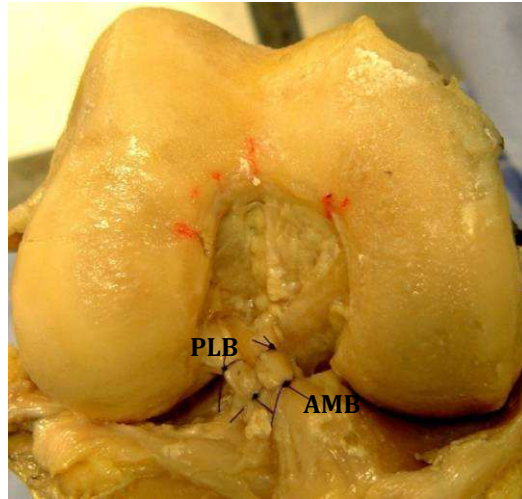


Figure2.8: AMB and PLB bundles separated

The AMB attachment occupies the proximal pole of the whole area, while the PLB one is in the distal aspect (Edwards, Bull Amis 2008). The attachment area of the two bundles is approximately the same (Harner, Baek, Vogrin et al 1999) (Fig. 2.9).

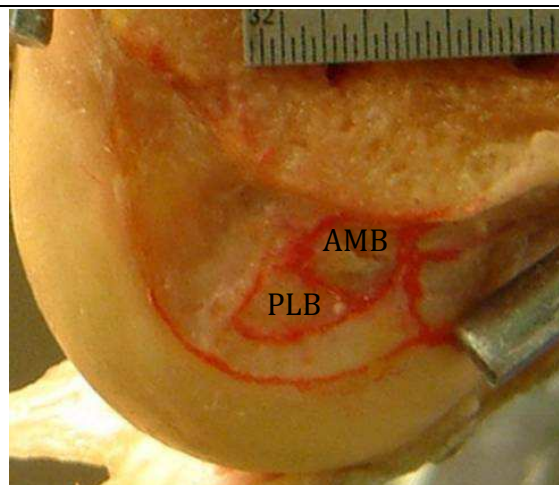


Figure2.9: AMB and PLB femoral attachment

Several authors have tried to relate the position of the bundle attachments to bony or soft tissue landmarks in order to facilitate the surgeon's task to perform an anatomical reconstruction.

Yasuda, Kondo, Ichiyama et al (2004), on cadaver knees, observed that the ACL attachment long axis diverged 30° from the femoral long axis. They also found that the centre of the PLB was 5 to 8 mm superior to the inferior aspect of the articular cartilage contour (Fig. 2.10). They therefore suggest that the surgeon should first mark the PLB centre attachment and then mark the AMB one as superior and on an axis diverging 30° from the femoral long axis.

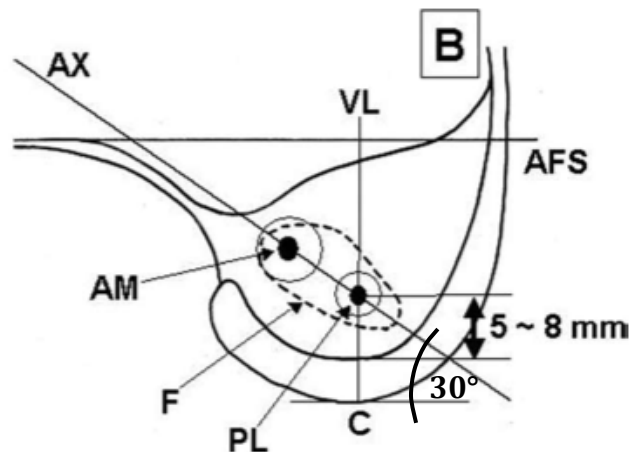


Figure 2.10: Yasuda's anatomic observations: the PLB attachment centre (C) is 5-8 mm superior than the most inferior aspect of articular cartilage contour

Yasuda's group anatomical landmarks have several limitations. First their observations were conducted on only five anatomic specimens with consistent interspecimen variability (up to 3 mm). Then, at arthroscopy, a 30° angulated axis with respect to the femoral one is difficult to identify without the inclusion of an appropriate additional measurement device.

In a larger cadaveric study including 50 specimens, Siebold, Ellert, Metz et al (2008) found that the angle between the ACL long axis and the femoral axis was 12° with the centre of the AMB 3-4 mm inferior to the over the top position. On a smaller but still consistent cadaveric series (22 specimens), Edwards, Bull, Amis et al (2007) found the mean ACL axis to be 37° divergent from the femoral long axis.

Ferretti, Ekdahl, Shen et al (2007), from the Pittsburgh group, described the existence of osseous landmarks to delimitate the native ACL attachment. They studied 16 cadaveric knees and found in all the specimens a ridge on the anterior

contour of the ACL attachment, which was named the lateral intercondylar ridge. From the lateral intercondylar ridge, a perpendicular and posteriorly directed ridge takes origin in 82% of the specimens. The latter was named the lateral bifurcate ridge and separates the attachment of the AMB from the PLB (Fig. 2.11).

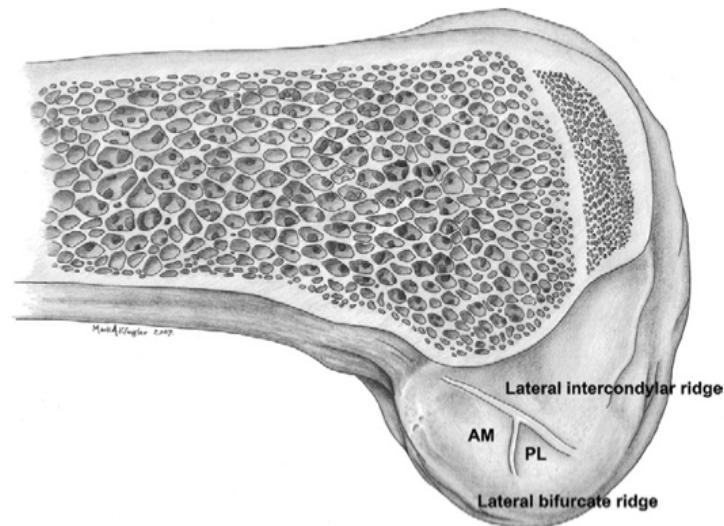


Figure 2.11: Schematic representation of Pittsburgh group bony landmarks (from Ferretti et al, 2007)

The lateral intercondylar ridge had been previously described by other authors (Hutchinson, Ash 2003) with a slight different location and orientation and was known as the Resident's ridge. The Resident's ridge, has been documented also by Purnell, Larson and Clancy (2008) by computed tomography and was described by them as the anterior limit of the ACL attachment.

Though consistent, the above described bony landmarks are not easily visualised at arthroscopy and confusion may arise among different prominences. It might have been the case that the name Resident's ridge was originally introduced to describe the osseous prominence which was often thought by the orthopaedic residents to be the posterior aspect of the lateral wall and then leading to a wrong tunnel placement. Furthermore Resident's ridge would describe only the anterior limit of the native attachment and its supporters (Ferretti, Ekdahl, Shen 2007; Purnell, Larson and Clancy 2008) do not provide any extra-information on where to place the centre of the femoral tunnels in the 113 mm² (Harner, Baek, Vogrin 1999) area beyond it.

From the above reported studies it is evident that no definitive landmarks of AMB and PLB attachments have been described. This has led some researchers (Colombet, Robinson, Christel et al 2006; Edwards, Bull, Amis 2008) to propose more complex systems to describe ACL bundle attachment positions, such as the Bernard quadrant method (Bernard, Hertel, Hornung et al 1997) or Amis circle method (Klos, Harman, Habets et al 2000). These methods inscribe the lateral wall in a rectangle (Bernard, Hertel, Hornung et al 1997) or in a circle segment (Klos, Harman, Habets et al 2000) and allow the bundle attachment positions to be located as a percentage of the rectangular side or of the circle diameter. Such systems have the advantage of by-passing the interindividual size variability but have the disadvantage of being too complex to be routinely employed at surgery. Thus, the above mentioned studies should provide the basic science information for more precise tunnel placement through computer navigation.

2.3.4 Anatomy of the Tibial ACL Attachment

The distal attachment of the ACL is located at the anterior intercondylar area of the tibia between the medial and lateral tibial plateaus, anterior to the tibial spines (Fig. 2.12). Its anterior limit reaches the transverse intermeniscal ligament.

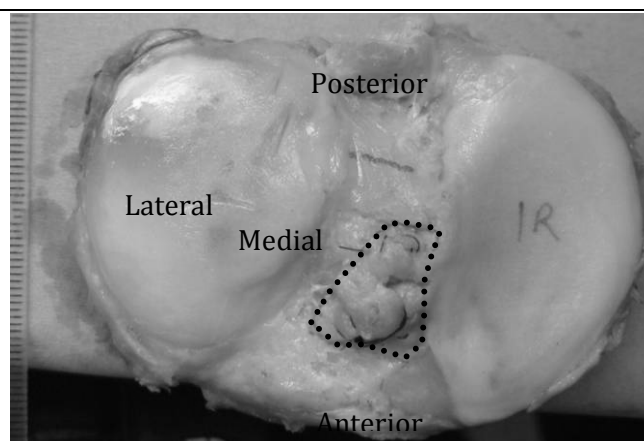


Figure 2.12: proximal view of the tibial ACL attachment (right knee)

The tibial ACL attachment can be difficult to identify arthroscopically. The ligament fibres attach to an area delimited in its lateral and anterior border by the anterior horn of the lateral meniscus. Posteriorly, the ACL insertion is bounded by the posterior horn of the lateral meniscus; medially the attachment is limited by the articular cartilage of the medial tibial plateau. In the sagittal plane the ACL attachment extends for 19 mm which is nearly twice the 10 mm width of the ligament at the proximal femoral insertion (Amis, Beynnon, Blankevoort et al 1994).

Several authors have tried to relate the AMB and PLB tibial attachments reproducibly to anatomical landmarks. Zantop, Wellmann, Fu et al (2008) in 20 cadaver knees employed as a landmark the centre of the anterior horn of the lateral meniscus and they found that the centres of the AMB and PLB were located 2.7 mm and 11.2 mm posterior and 5.2 mm and 4.1 mm medial to it, respectively. Their findings were quite consistent, with standard deviations within 1 mm. Conversely, the main limitation of this investigation is that the authors omitted to define a reference axis for their measurements.

Siebold, Ellert, Metz et al (2008), assumed as landmarks the anterior border of the ACL and the medial and lateral border of the lateral and medial plateau articular cartilage. The AMB centre was 5 mm posterior to the anterior ACL margin and 3 mm lateral to the lateral border of the medial plateau. The PLB centre was 6 mm posterior to the ACL anterior limit and 2 mm medial to the medial border of the lateral plateau. These authors also omitted to define a reference axis. Furthermore, the landmarks they propose are not easily identified at arthroscopy as the ACL stump is often missing or altered by the chronicity of the lesion. Finally, an anterior landmark, like the anterior ACL limit can expose the graft to roof impingement as will be discussed in Chapter 6.

Edwards, Bull and Amis (2007), in 55 cadaver knees, referred the AMB and PLB tibial attachments position to the over the back, defined as the initiation of the posterior slope of the tibial plateau that sits just anterior to the posterior cruciate ligament (Hutchinson, Bae 2001) and assuming as a posterior reference axis the line connecting the posterior limits of the medial and lateral condyles. The centre of the PLB and AMB were found to be 10 and 17mm anterior to the over the back

position and 4 and 5 mm lateral from the lateral border of the medial tibial spine, respectively. The standard deviations were all less than 2 mm. These latter observations have the advantage of being related to bony rather than soft tissue landmarks.

2.3.5 Experimental Study on AMB and PLB Attachments

Based on the literature review above, it was found that no consensus exists on ACL bundle attachment landmarks with variability in terms of orientation, bony landmarks and position. Therefore, the aim of this initial investigation was to study ACL bundle attachment anatomy in cadaver knees and use the new information for the surgical and clinical studies which will be illustrated in the following chapters.

Twenty one fresh-frozen human cadaveric knees were employed in this study. They had been obtained with informed consent from relatives in accordance with local research ethics committee permission. Specimens were thawed at room temperature for 12 hours before testing. All the extra-capsular soft tissues were removed completely, including the extensor apparatus. The ACL and the posterior cruciate ligament (PCL) were intact and competent in all the specimens. The collateral ligaments were intact or repaired in all the cases and all knees showed no abnormal laxities in extension.

The AMB and PLB of the ACL were identified on a functional basis applying an anterior drawer at 90 degrees which tightened the AMB while the PLB was relaxed. In this loading condition the two bundles can be separated by blunt dissection (Edwards, Bull and Amis 2007). The ACL was then cut in its midsubstance and the tibial attachments of the two bundles were identified and marked with red ink after the remnants of the bundles had been peeled from the bone. The “over the back position” was marked as well.

Femur methods: in order to properly identify and mark the femoral attachments of the bundles, the lateral femoral condyle was split from the medial condyle and

from the diaphysis. The femoral part of the study was performed in 14 knees and the lateral wall of notch was photographed. Two pictures of the notch were obtained: one with the camera perpendicular to the ACL attachment in order to have the widest image of the attachment (attachment view), and one perpendicular to the femoral shaft in a medial-lateral direction (notch side view) (Fig. 2.13).

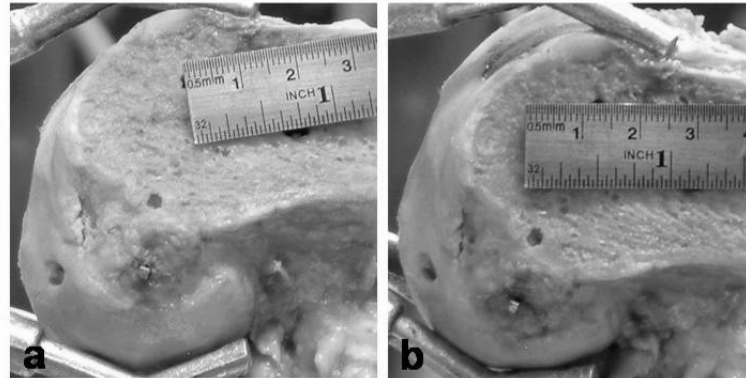


Figure 2.13: a) attachment view, obtained with camera perpendicular to the attachment; b) notch side view, obtained with the camera perpendicular to the condyle section.

In the attachment view images, the dimensions of the attachment were measured. In the notch side view the positions of the centre of the AMB and PLB attachments were measured according to the Amis circle method (Klos, Harman, Habets 2000) which relates the percentage position of a point in the notch to the circle formed by the posterior and distal contours of the lateral femoral condyle assuming the most inferior and shallow points of the circle as 0% and the most superior and deep as 100% with the shallow-deep axis parallel to the notch roof (Fig. 2.14). This method has the advantage to by-pass interspecimen size variability using the circle as a normalising tool.

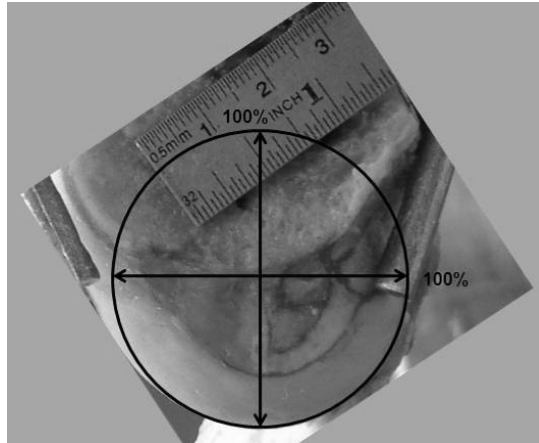


Figure 2.14: Amis circle method: a circle fits the posterior condyle contour with its shallow-deep axis aligned to the roof of the notch. The most superior and deep points are defined as 100% positions.

Tibia methods: 21 knees were available. The tibial plateau was photographed with a Nikon Coolpix digital camera. A ruler was positioned on the tibial plateau to provide a physical measurement scale. A Steinmann pin was held aligned with the posterior aspect of the tibia and was defined as the posterior axis of the tibia. The pictures from all the plateaux were downloaded to a personal computer and analysed with Office XP Powerpoint software (Microsoft Corporation). All the images were normalised in size and adjusted to be right sided.

The position of the ACL attachment in the AP direction with respect to the over the back position and in the medio-lateral direction relative the lateral aspect of the medial tibial spine was calculated. The positions lateral to this axis were defined as be positive, the medial ones were negative values. The border between the AMB and PLB along the medial and lateral sides of the ACL attachment were also calculated.

Femur results: the ACL femoral attachment, measured in the attachment view, was 18 mm (SD 2; range 14-22) long and 9 mm (SD 1; range 8-11) wide. The border between the AM and the PL bundle attachments was at 54 ± 12 (36-73)% of its shallow aspect and at 56 ± 10 (41-74)% of the deep aspect.

The posterior part of the lateral femoral condyle fitted a circle with diameter 39 ± 4 (35-47) mm. The shallow-deep and infero-superior positions of the centre of the AMB attachment were 69 ± 5 (55-77)% and 50 ± 7 (34-59)% respectively. The

PLB attachment centre was $61 \pm 4 (53-67)\%$ deep and $37 \pm 6 (25-42)\%$ superior. A scatterplot of the centres of the 2 bundles is presented in Fig. 2.15.

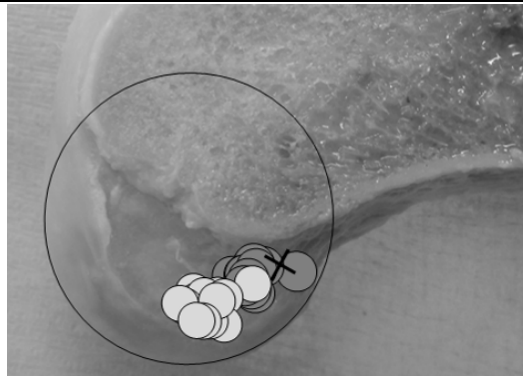


Figure 2.15: scatterplot of the attachments of the AMB (grey circles) and PMB (white circles) according to the Amis circle method (Klos 2000)

Tibia results: the anterior and posterior limits of the tibial ACL attachment were at 22 mm mean $\pm$ 3 mm SD, range 16-27 mm and 6 $\pm$ 2 (2-8) mm respectively anterior from the over the back position. The medial and lateral limits of the attachment were at 3 $\pm$ 1 (2-5) mm medial and 6 $\pm$ 2 (3-9) mm lateral from the sagittal axis.

The tibial attachment was on average 17 $\pm$ 2 (12-19) mm long and 9 $\pm$ 2 (7-16) mm wide. The border between the PL and AM attachments was at 11 $\pm$ 2 (8-14) mm on the medial side and at 17 $\pm$ 4 (11-24) mm on the lateral side from the 'over the back' position. In percentage terms the medial border between the bundle attachments was at 33 $\pm$ 12 (12-58) % of the attachment length while the lateral while the lateral was at 68 $\pm$ 14 (47-94)%.

In Fig. 2.16 a schematic representation of the 21 tibial attachments is presented.

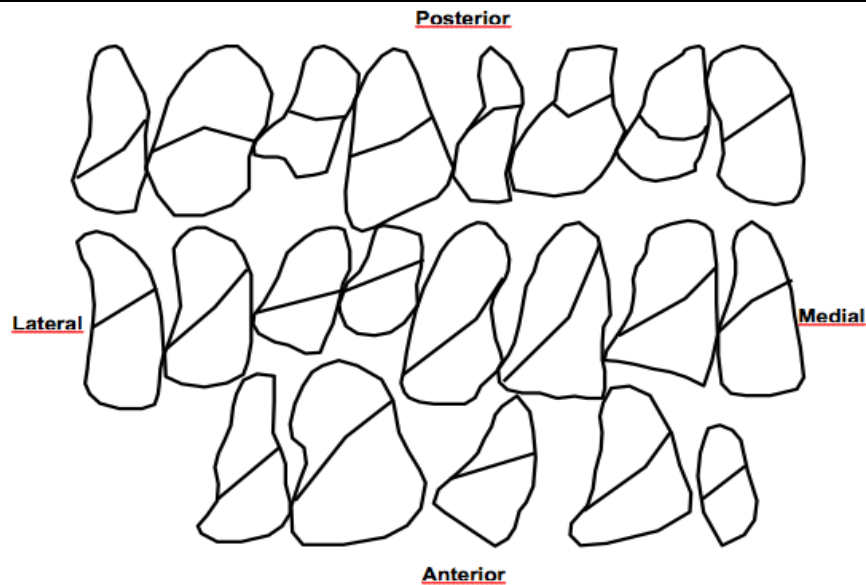


Figure 2.16: the 21 normalised attachments are presented. A central line divides the AMB and PLB

2.3 Conclusions

In this chapter, the gross anatomy of the ACL was described, particularly in relation to its main functional bundles, the AMB and PLB. Then a literature review on the bundle attachment sites, mainly in terms of location and orientation, was performed. It is evident that no agreement has been achieved so far on bundle attachment bony landmarks that can be employed at surgery. Furthermore high variability in bundle attachments location and orientation has been documented leaving the field open for further investigations and surgical systems, including computed navigation.

A cadaver study on AMB and PLB tibial and femoral attachment locations was performed and its results presented. Particularly on the femur, despite the employment of a normalising method like the circle, high variability in attachment location was observed. On the tibia high variability in size was observed as well. This can be ascribed to interindividual variability in attachment size and shape but also to the different sagittal plane orientation of the anterior intercondylar fossa

which could lead to an over or under estimation of the size itself due to the limitation of a two-dimensional digital picture taken perpendicular to the tibial plateau. Furthermore a repeatability study was not performed as the red ink employed to demarcate the attachment contour was not deletable.

The methodology employed in the study suffers the drawbacks of in vitro studies and its utility for the surgeon may seem limited as no anatomic representation of the entire femur nor arthroscopic views were presented, anyway this study will serve as a basis for further biomechanical and surgical tests that will be presented in the following chapters.

Chapter 3 – ACL Contribution to the Control of Knee Laxity

In Chapter 2 the anatomy of the ACL was described and the recent literature on its main bundles reviewed. In this chapter the role of the ACL in controlling knee motion is explored in a laboratory study and the results will be then discussed and compared with those from the existing literature.

3.1 Introduction

The contribution of the ACL to the control of knee motion has been investigated widely with various techniques and under different conditions (Amis 1989; Amis, Dawkins 1991; Andriacchi, Dyrby 2005; Brandsson, Karlsson, Eriksson 2001; Dennis, Mahfouz, Komistek 2005; Fukubayashi, Torzilli, Sherman et al 1982; Gabriel, Wong, Woo et al 2004; Georgoulis, Papadonikolakis, Papageorgiou et al 2003; Gollehon, Torzilli, Warren et al 1987; Haimes, Wroble, Grood et al 1994; Lane, Irby, Kaufman et al 1994; Lipke, Janecki, Nelson et al 1981; Markolf, Bargar, Shoemaker et al 1981; Nielsen, Helmig 1985; Reuben, Rovick, Schrage et al 1989; Seering, Piziali, Nagelet al 1980; Shoemaker, Markolf 1985). The ACL has been demonstrated to control mainly transverse plane knee motion, being the primary restraint of tibial anterior translation. Some studies demonstrated a role of the ACL in controlling the limits of tibial internal-external rotations (Fukubayashi, Torzilli, Sherman et al 1982; Lipke, Janecki, Nelson et al 1981, Markolf, Bargar, Shoemaker et al 1981, Seering, Piziali, Nagelet al 1980, Shoemaker, Markolf 1985), but some others did not (Gollehon, Torzilli, Warren et

al 1987; Haimes, Wroble, Grood et al 1994; Lane, Irby, Kaufman et al 1994, Nielsen, Helmig 1985; Reuben, Rovick, Schragar et al 1989). On the other hand, in vivo the ACL prevents the pivot shift phenomenon, a translatory and rotatory movement (Bull, Andersen, Basso et al 1999; Kanamori, Zeminski, Rudy et al 2002; Leitzel, Losee, Jokl 2005) and ACL insufficiency causes knee instability, which is referred to by patients as a giving-way sensation (Irrgang, Anderson, Boland 2001). These clinical findings are suggestive of a role of the ACL in influencing knee rotations.

The concepts of “motion limits” and “coupled motions” have been described in the past and applied to define the contribution of different structures to knee motion. The first - more strictly, a laxity limit - means the position of the tibia in relation to the femur when an external load is applied (Haimes, Wroble, Grood et al 1994). The latter is the motion which occurs in a degree of freedom that is different from the degree of freedom of an applied external load (Gollehon, Torzilli, Warren 1987). For the ACL, this phenomenon is most commonly recognised as a tibial internal rotation resulting from application of an anterior translation (drawer) force (Bull, Andersen, Basso et al 1999). Previous ACL investigations have not analysed all the transverse plane coupled motions under all the possible loading combinations, but it is known that the pivot-shift test induces a combination of tibial anterior translation and internal rotation (Butler, Noyes, Grood 1980).

Hence a laboratory study has been designed with the following purposes: 1) to describe a system to measure six degrees of freedom (6DOF) primary and coupled knee motions under different loading conditions and 2) to employ it to revisit the function of the ACL. In particular, it was hypothesised that ACL transection would cause significant changes in the envelopes of tibiofemoral laxity when combinations of drawer forces and internal-external torques, such as anterior drawer plus internal rotation, were imposed.

3.2 Material and Methods

Seventeen fresh frozen cadaver knees from consented donors (mean age: 64.5 years old; range 48-74) were obtained from a tissue bank in conformity with a Local Research Ethics Committee permit and related legal requirements. They were thawed overnight before use. Approximately 20cm of thigh and shank were available in each specimen. The skin and the muscles were not removed. The fibula was secured to the tibia in its anatomical position with cortical screws and a 40cm long aluminium rod was fixed with bone cement in the tibial medullary canal and secured with additional transverse screws. The femoral end was cemented in a tubular steel pot aligned coaxial with the tibial intramedullary rod while the knee was held in full extension with the tibial rod vertical (Fig. 3.1). This minimized the varus-valgus moment during passive flexion-extension. The steel pot was removed from the bone cement cylinder.



Figure 3.1: a knee potted in the vertical position to minimise varus-valgus moment

The femoral cement cylinder was secured in a non ferromagnetic rig which allowed manual passive knee flexion-extension by moving the femur with the unconstrained tibia hanging vertically (Fig. 3.2).

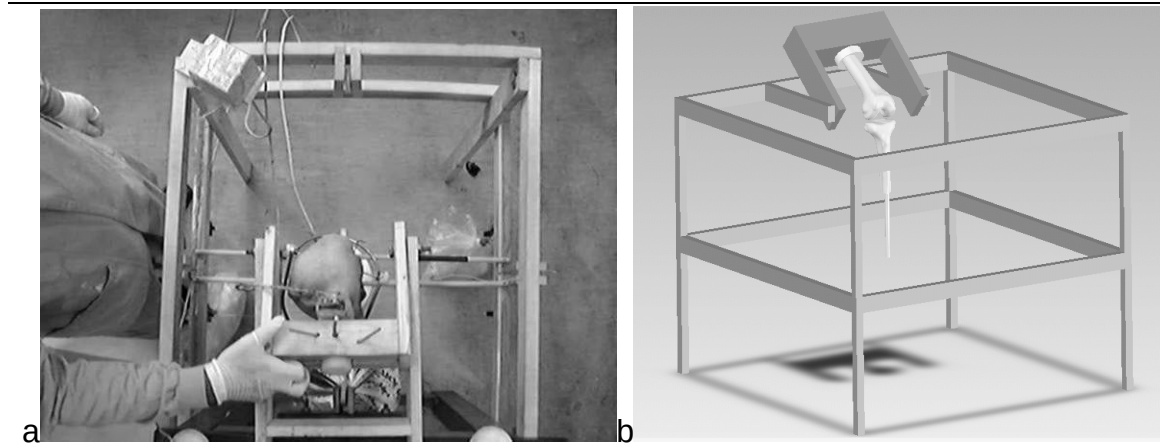


Figure 3.2: a) top-view of the wooden non-ferromagnetic rig; b) specimen position in the rig is adjusted to match knee and rig flexion-extension axis. Manual passive flexion-extension movements are applied to the femur.

A transverse Steinmann pin was drilled mediolaterally across the proximal tibia perpendicular to the shaft and fixed to two semicircular hoops (one anterior and one posterior) which could be connected to weights via pulleys and strings, resulting in an anterior or posterior tibial force without inhibiting or inducing tibial rotation (Fig. 3.3).

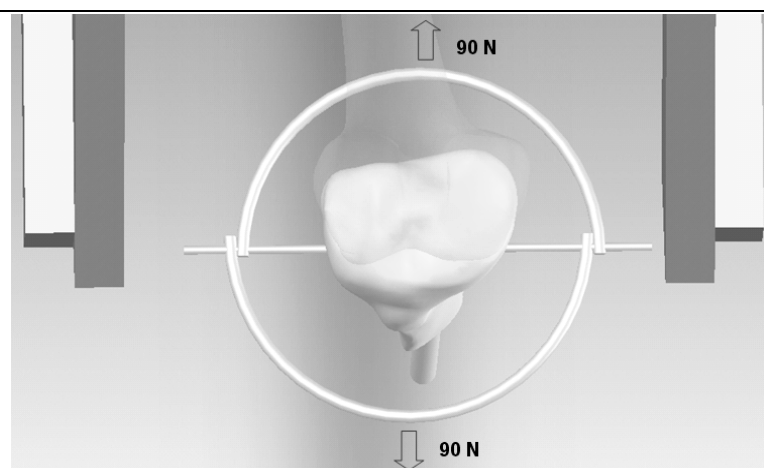


Fig. 3.3: The anterior or posterior force is applied with weights connected to the tibia.

A polyethylene disc (Ø 20 cm) was applied to the distal end of the tibial rod. Weights connected via pulleys and strings to opposite poles of the disc resulted in an internal or external rotation torque (Fig. 3.4).

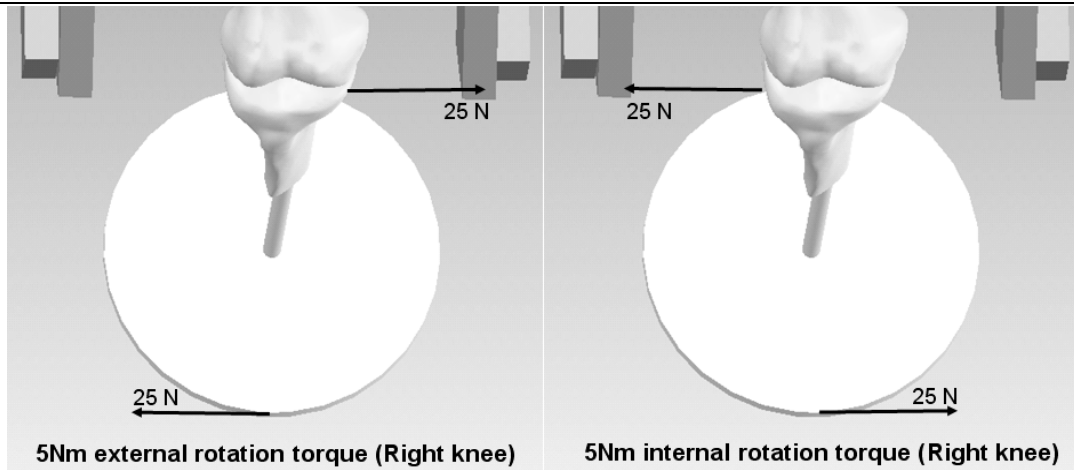


Figure 3.4: Internal or external rotation torque is applied with weights connected to both sides of a polyethylene disc secured at the end of the tibial rod.

6DOF knee motion was measured with an electromagnetic device (Nest of birds, Ascension Technology, Burlington, VT) whose accuracy had been validated previously (Bull, Berkshire, Amis 1998) and found to be $\pm 0.06\text{mm}$ in a 30mm translation and $\pm 0.4^\circ$ in a 20° rotation. The system consisted of a magnetic field transmitter and three sensors.



Figure 3.5: Nest of Birds system, consisting of one magnetic transmitter and three sensors

Two sensors were press-fitted into custom made mounting blocks which had previously been fixed rigidly to the femoral and tibial shaft with screws and bone cement. The third sensor was instrumented with a stylus and calibrated to digitise bony landmarks (Fig. 3.6). All the equipment employed in the study was tested to ensure that they were non ferromagnetic and that they did not interfere with the electromagnetic measuring system.



Figure 3.6: the digitising sensor instrumented on a calibrated stylus

After exposing the medial femoral epicondyle through a standard medial parapatellar approach its centre was digitised. The apex of the lateral epicondyle was digitised after exposing it through a limited lateral approach to the distal femur. The centre of the proximal femoral medullary canal was then digitised to calculate the femoral anatomical axis. All bony landmarks were digitised with the knee in extension and the relative position of the tibia to the femur at this moment was defined as zero. The position of 0 degrees extension was defined when the tibial intramedullary rod was parallel to the potted shaft of the femur in the sagittal plane. This position was preferred to the full-extension in order to avoid interspecimen variability particularly with regard to hyperextension which could occur in some knees due to physiologic laxity and affect graft tension at the time of ACL reconstruction (Chapter 4 and 5). The transepicondylar axis was defined as the knee flexion-extension axis and tibial rotations and displacements were described relative to its mid-point. All six DOF were quantified using the three-cylinder open chain mechanism according to Grood and Suntay (1983). For our purposes flexion/extension, anteroposterior translation and internal/external rotation were analysed (Fig 3.7)

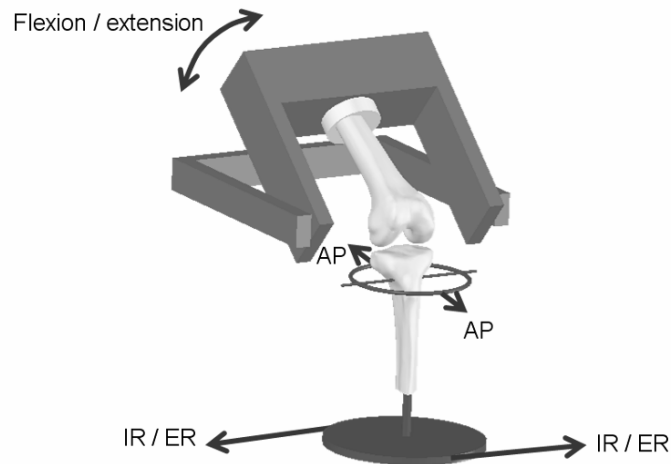


Figure 3.7: 6DOF motion was possible. For this study purposes only sagittal and transverse plane rotation and anteroposterior translation were analysed

The envelope of tibial antero-posterior and rotational motion through the range of knee flexion-extension was recorded in 9 different loading conditions resulting from the combination of a 90N anterior or posterior drawer force and a 5Nm internal or external rotation torque applied to the tibia: 1) anterior force (condition A); 2) anterior force and internal torque (condition AI); 3) anterior force and external torque (condition AE); 4) internal torque (condition I); 5) external torque (condition E); 6) posterior force (condition P); 7) posterior force and internal torque (condition PI); 8) posterior force and external torque (condition PE); 9) no force (condition N), i.e. the tibial assembly hanging freely from the femur.

The displacement and angular precision of the setup were calculated as the difference in antero-posterior and internal-external rotation position at every degree of knee flexion between two consecutive full flexion cycles under the AI loading condition in all the knees.

The envelope of knee motion was recorded in the intact knee and after the complete removal of the ACL from the intercondylar notch. First flexion cycle data were analysed. Continuous data were interpolated to single degree of flexion increments and analysed using SPSS 13.0 for Windows (SPSS Inc., 1989-2004). Tibial rotations and translations from each loading condition were normalised to the anteroposterior and rotational position of the intact knee in the N loading condition at each degree of knee flexion by simple subtraction. Mean differences

and 95% confidence intervals of the differences between ACL deficient and intact knee translations and rotations were calculated at single degree of flexion increments and plotted. It was assumed, according to the sign test, that when the confidence interval of a difference did not change sign, then the difference was statistically significant ($p < 0.05$). Furthermore Pearson's correlation coefficients between translation and rotation changes were calculated at 20 degrees of flexion intervals.

3.3 Results

Of the 17 knees used, 2 were used when developing the testing protocol and were excluded and 1 knee was excluded because a complete ACL rupture was observed at visual inspection after the arthrotomy. The results from the remaining 14 specimens are presented here.

The system rotation and translation differences between 2 consecutive knee flexion cycles in the AI loading condition were $0.1^\circ \pm 0.3$ ($-0.95 - 1.1$) (mean $\pm$ 1 SD, range) and $0.0 \text{ mm} \pm 0.4$ ($-2 - 2.3$), respectively.

The envelopes of laxity for anterior/posterior drawer loads with the ACL intact are shown in Fig. 3.8, where the horizontal axis, zero anteroposterior translation, represents the unloaded neutral (N) condition. The greatest posterior laxity, across the range 0° to 100° of knee flexion, resulted from a posterior drawer force with the tibia free to rotate (line P). The addition of an internal (PI) or external (PE) rotation torque reduced the posterior laxity, as expected. This effect was strong enough to prevent the tibia moving posteriorly significantly beyond the neutral position from approximately 5° to 35° flexion if simultaneously held in internal rotation (PI).

A similar picture emerged for tibial anterior drawer when the knee flexed more than 45° : the greatest anterior translation resulted from an anterior drawer force with free tibial rotation (condition A), with reduced laxity if combined with internal

(AI) or external (AE) rotation torques. Nearer to knee extension, however, Figure 3.8 shows that tibial external rotation (condition E and AE) induced a coupled anterior translation as large as that caused by the anterior drawer force.

If the effects of isolated tibial rotation torques are examined, it is seen that tibial external rotation (condition E) had induced a coupled tibial anterior translation near knee extension, an effect that had disappeared by 70° of flexion. Conversely, tibial internal rotation (I) had induced a tibial posterior translation across the range 0°-100° examined. Taken together, these findings suggest that the medial compartment was more mobile than the lateral from 0° to approximately 65° of flexion.

Figure 3.9 shows the effects of different loads on tibial rotation laxity. Again, the zero axis represents the neutral (N), unloaded condition. It is clear that the greatest internal and external rotations were caused by imposing internal (I) and external (E) rotation torques alone. These rotational laxities were reduced when both anterior or posterior drawer forces were combined with the rotation torques (PE, AE or PI, AI). The imposition of isolated anterior (A) or posterior (P) drawer forces had induced small tibial coupled internal or external rotations, respectively.

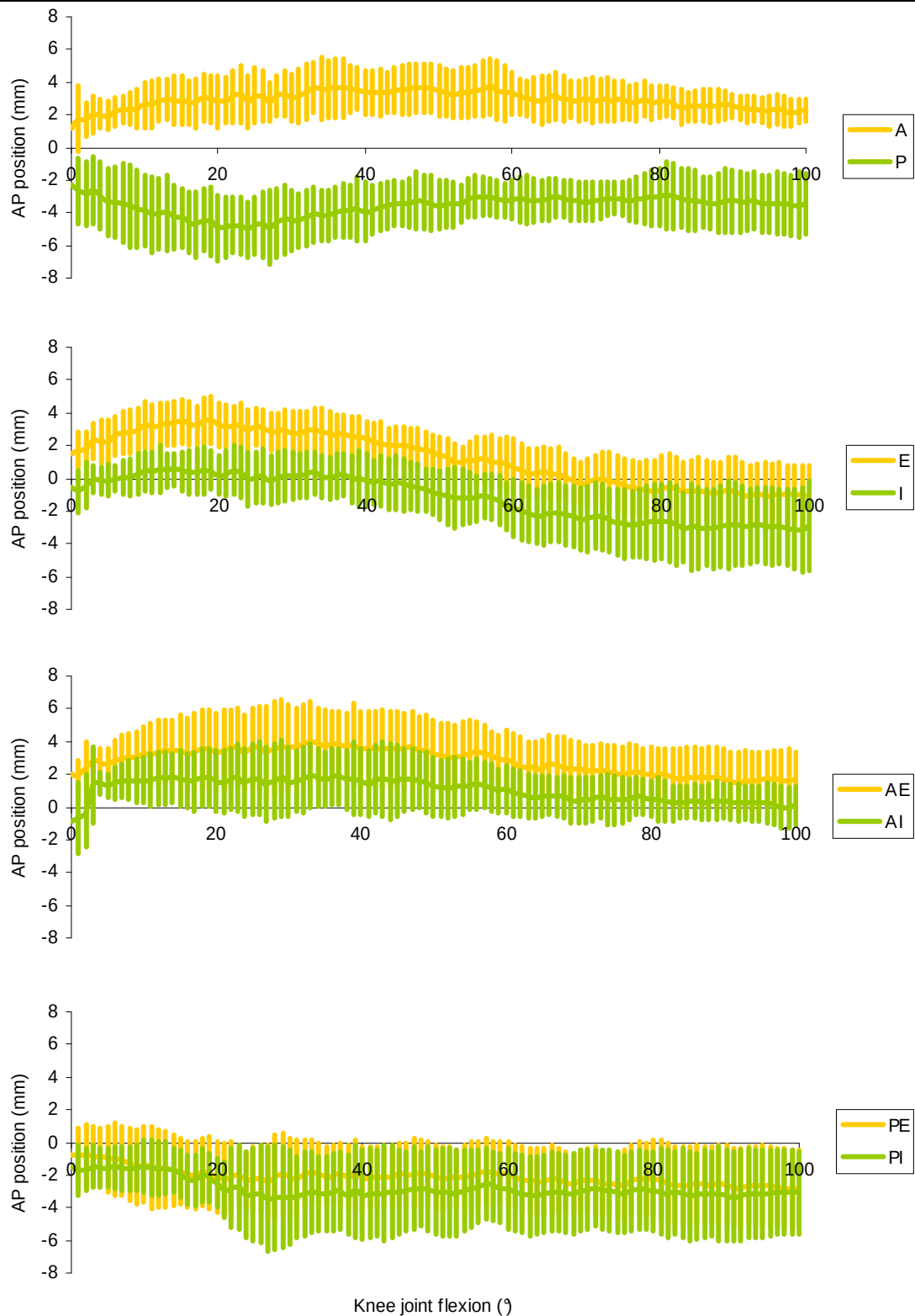


Figure 3.8: The envelope of mean intact knee translations (± 1 SD) with flexion, normalised to the anteroposterior position in the Neutral loading condition (A= 90N anterior force; P= 90N posterior force; I= 5Nm internal rotation torque; E= 5Nm external rotation torque).

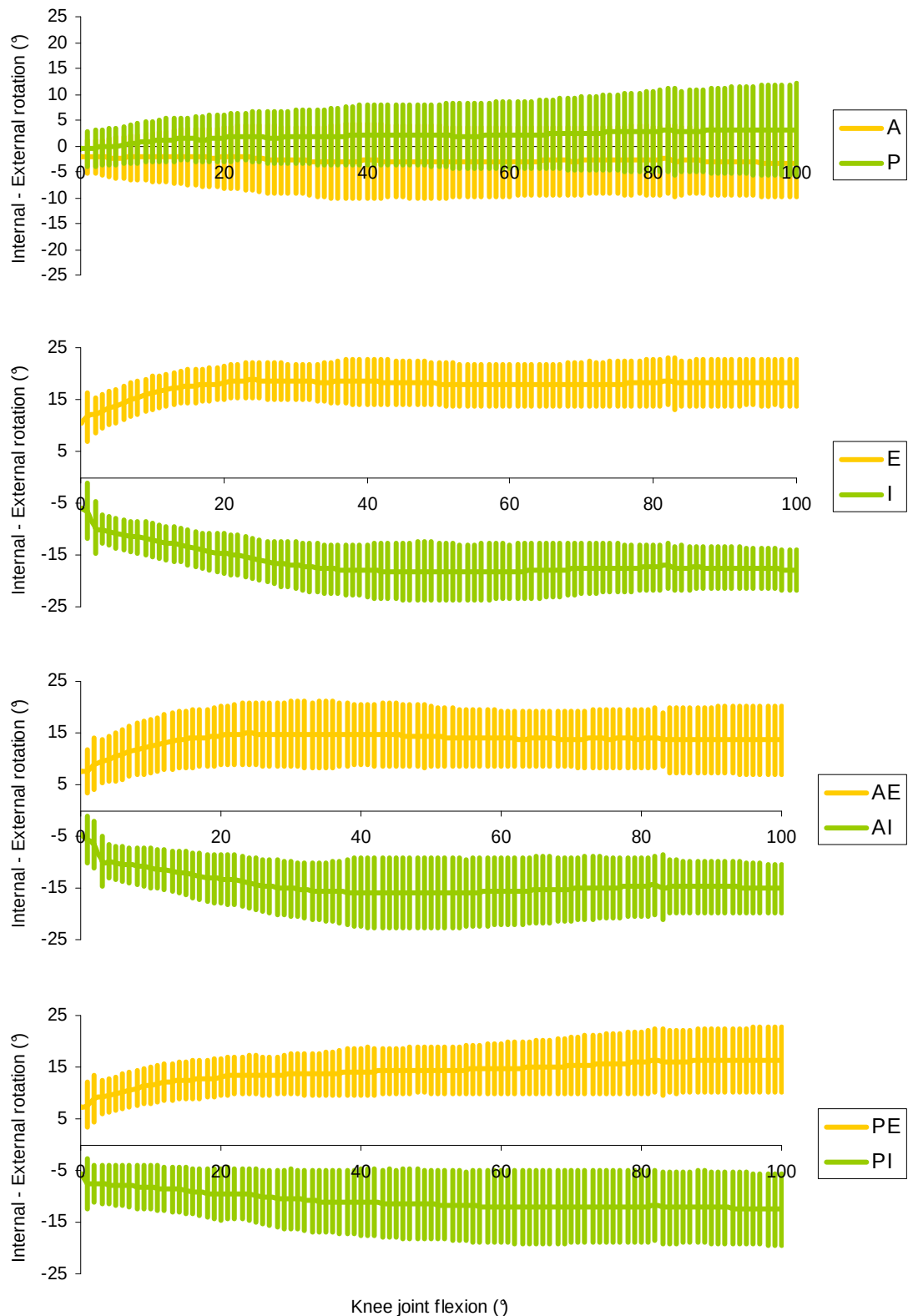


Figure 3.9: The envelope of average intact knee rotations (± 1 SD) with flexion, normalised to the rotational position in the Neutral loading condition. Positive values mean external rotation. (A= 90N anterior force; P= 90N posterior force; I= 5Nm internal rotation torque; E= 5Nm external rotation torque).

Figures 3.10, 3.11 and 3.12 show the effect on anteroposterior laxity caused by cutting the ACL, for the 9 loading conditions. In each graph, the baseline is the intact behaviour, that was shown in Figure 3.8. The change in laxity after cutting the ACL is shown as mean $\pm$ 95% C.I. so if that C.I. is completely above or below the axis there has been a significant change in anteroposterior laxity. Figure 3.11 shows that, for the neutral (unloaded) state, cutting the ACL had allowed the tibia to move anteriorly. This was significant from 0° to 100° of flexion, but from 0° to 40° flexion the neutral position had shifted by a mean of approximately 4mm anteriorly. As expected, the increase in anterior laxity, in response to an anterior drawer force, was highly significant across the range of flexion, with the largest increases, approximately 9mm, around 15°-30° knee flexion (Fig. 3.10). Cutting the ACL did not cause a significant effect on tibial posterior translations, as expected (Fig. 3.12).

The coupled tibial anteroposterior translations induced by imposing internal-external rotation torques were shifted anteriorly by cutting the ACL. This effect was significant from 0° to 40° of flexion (Fig. 3.11). For the intact knee, external rotation (E) had induced tibial anterior translation, so cutting the ACL increased this effect significantly. Conversely, internal rotation (I) had induced tibial posterior translation, so cutting the ACL had reduced this significantly from 0° to 40° of flexion. Combinations of anterior drawer force plus tibial rotation torques allowed significant increases of anterior translation laxity, but it is also clear that these changes were smaller than for the “pure” anterior drawer force with free tibial rotation (Fig. 3.10).

The effects of cutting the ACL on tibial rotation are shown in Figures 3.13, 3.14, 3.15. The principal observation is that cutting the ACL had allowed only small changes in tibial rotational laxity. For example: although the change in tibial internal rotation in response to an isolated internal rotation torque (I) was statistically significant across the range of flexion, the change in laxity of approximately 2°-3° would not be likely to be detectable in a live knee. Cutting the ACL had no significant effect on the coupled rotations that accompanied anterior or posterior translation (drawer) forces.

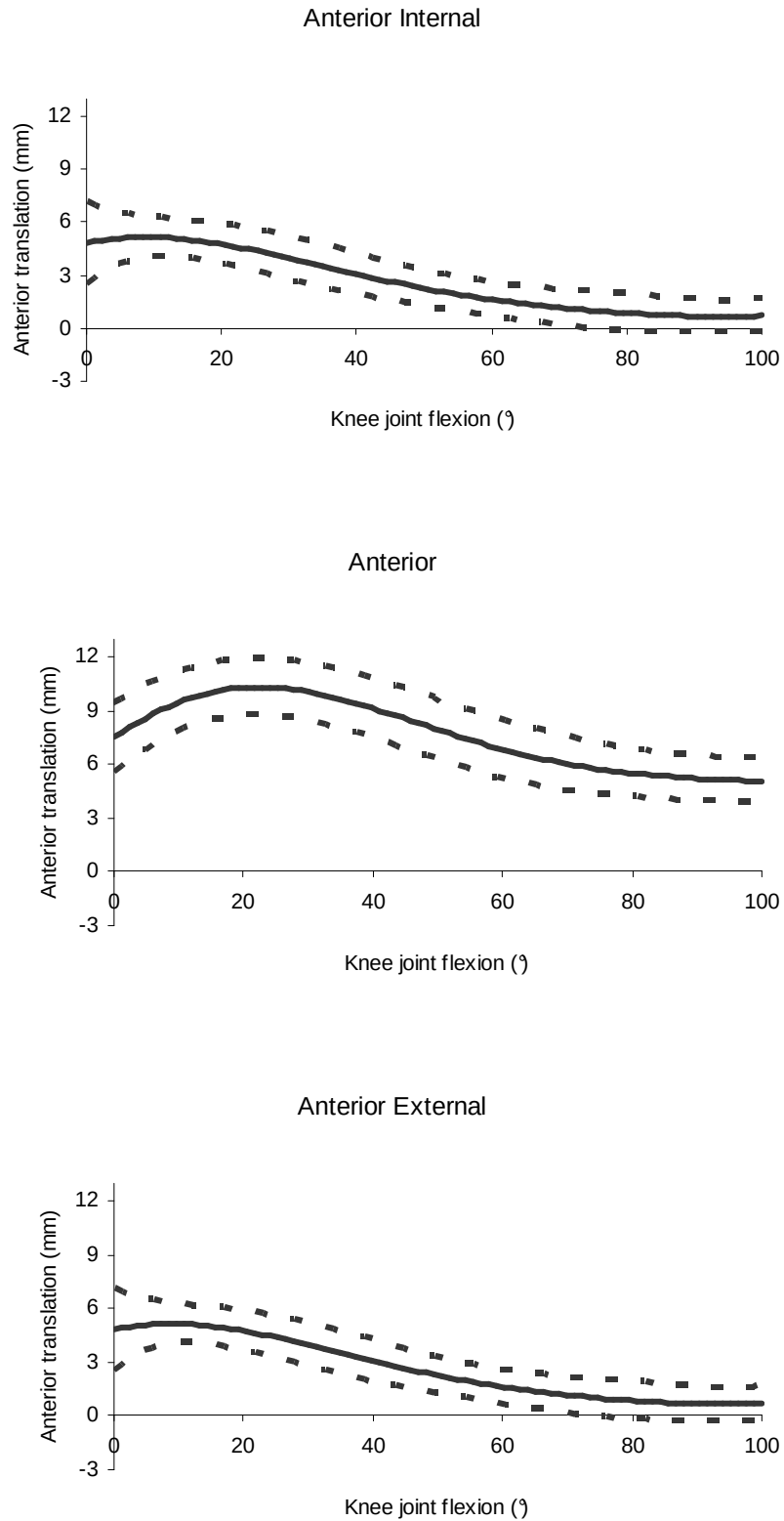


Figure 3.10: Mean changes in anterior tibial displacement after ACL section (continuous lines) and 95% confidence interval limits (dotted lines) in the anterior drawer (90N) conditions.

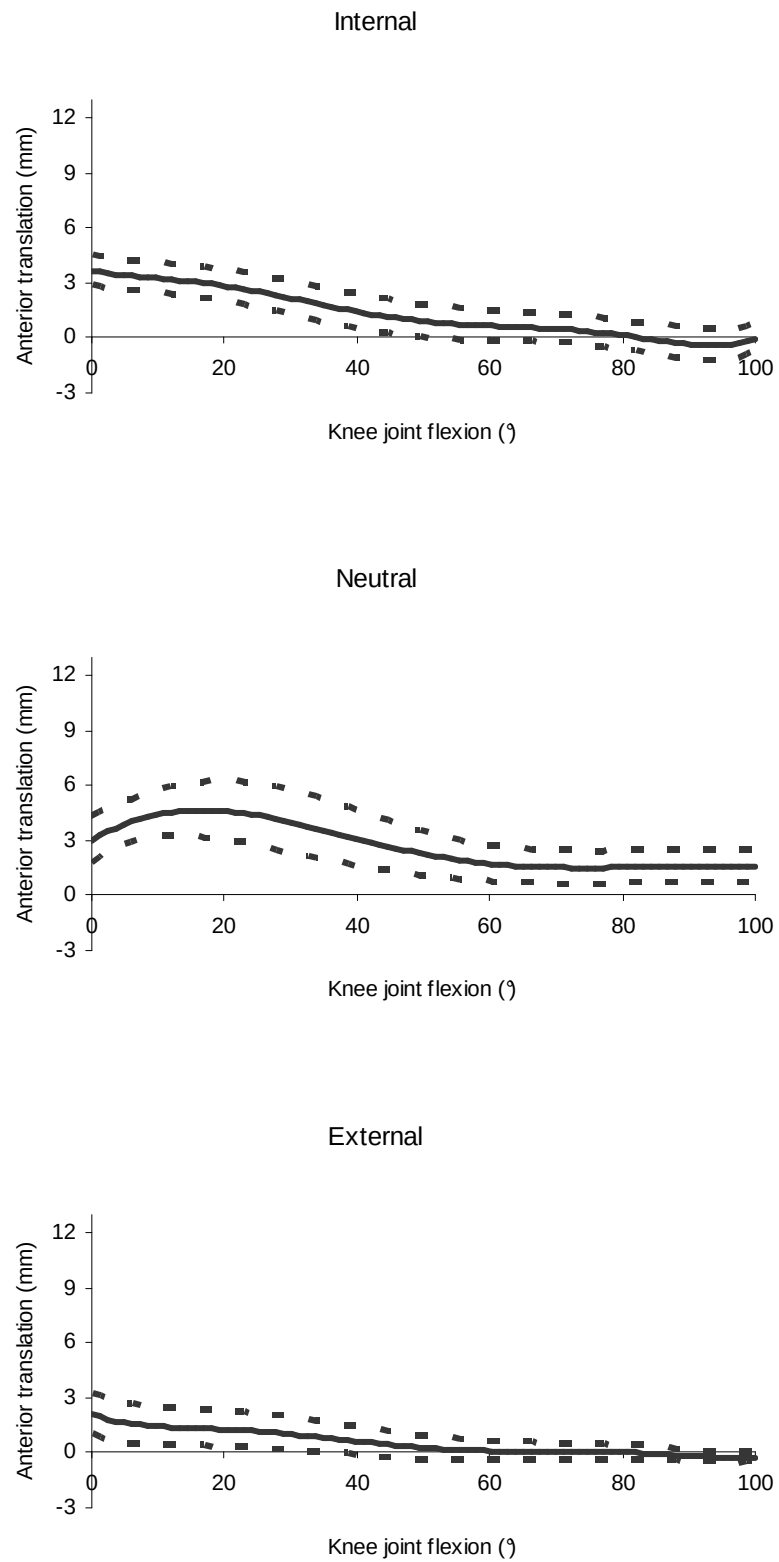


Figure 3.11: Mean changes in anterior tibial displacement after ACL section (red lines) and 95% confidence interval limits (dotted lines) without any applied drawer force.

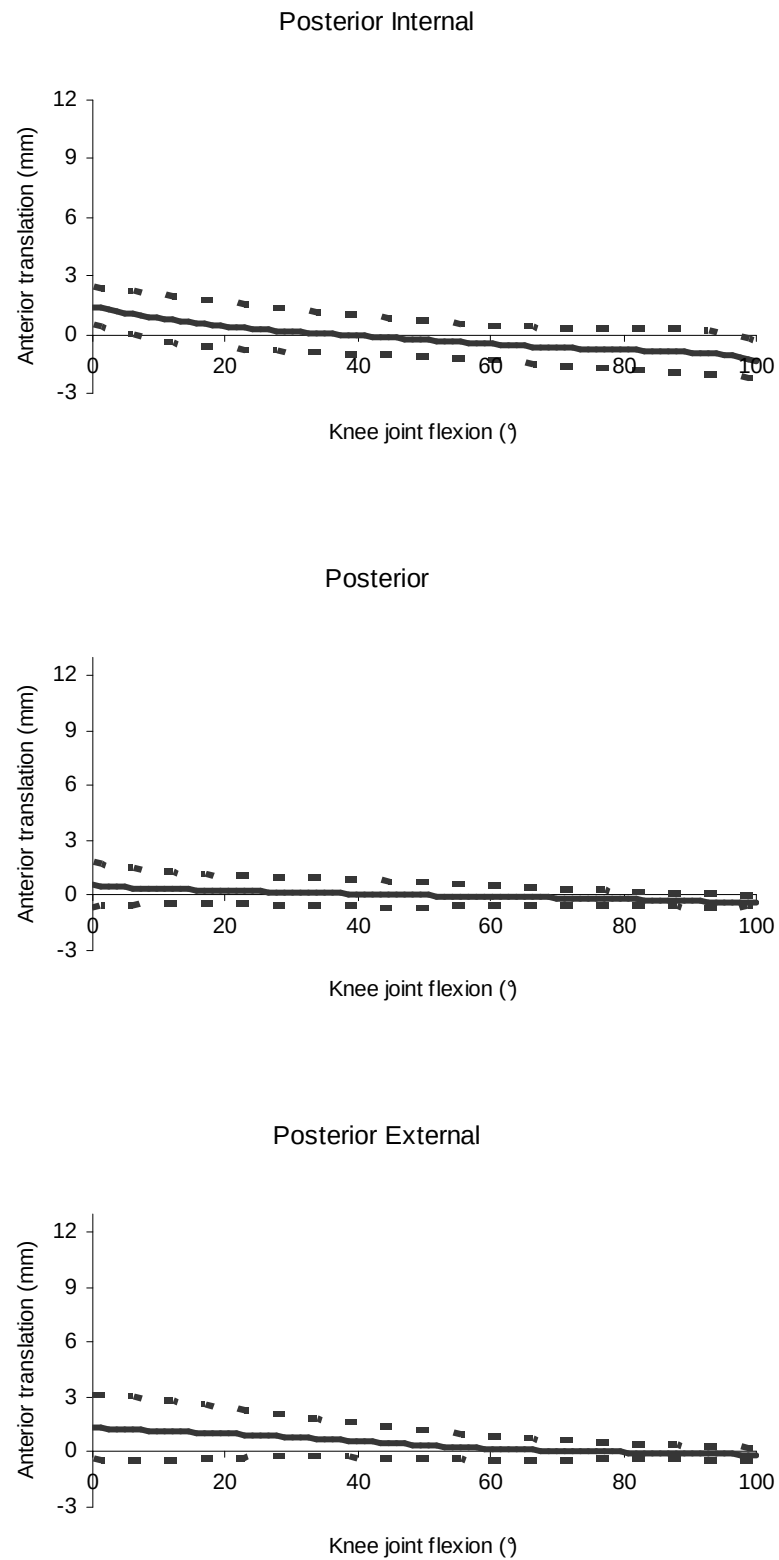


Figure 3.12: Mean changes in anterior tibial displacement after ACL section (continuous lines) and 95% confidence interval limits (dotted lines) in the posterior drawer (90N) conditions.

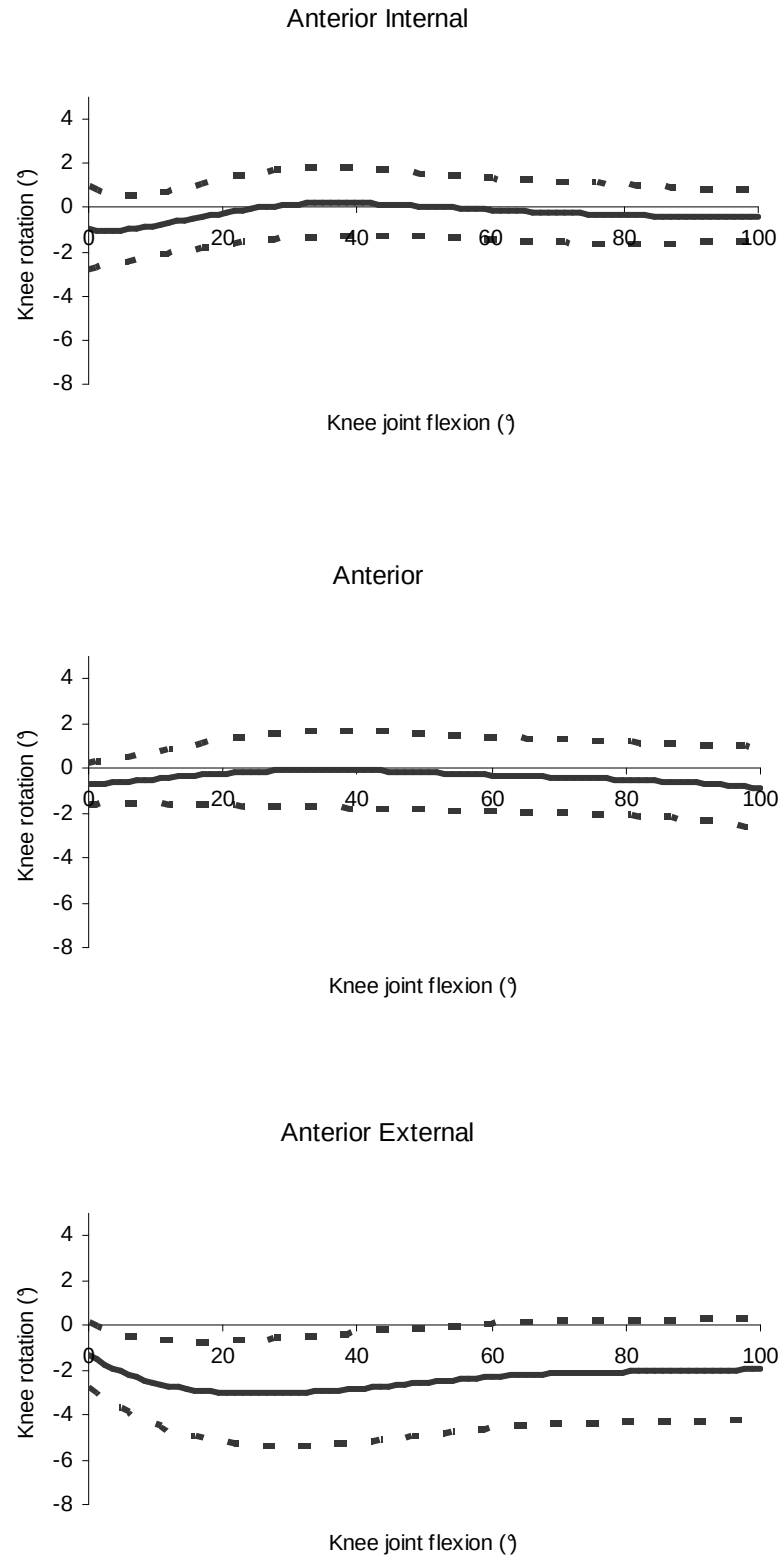


Figure 3.13: Mean changes in rotations after ACL section (continuous lines) and 95% confidence interval limits (dotted lines) under anterior drawer (90N) conditions. Positive values mean external rotation, negative values internal rotation.

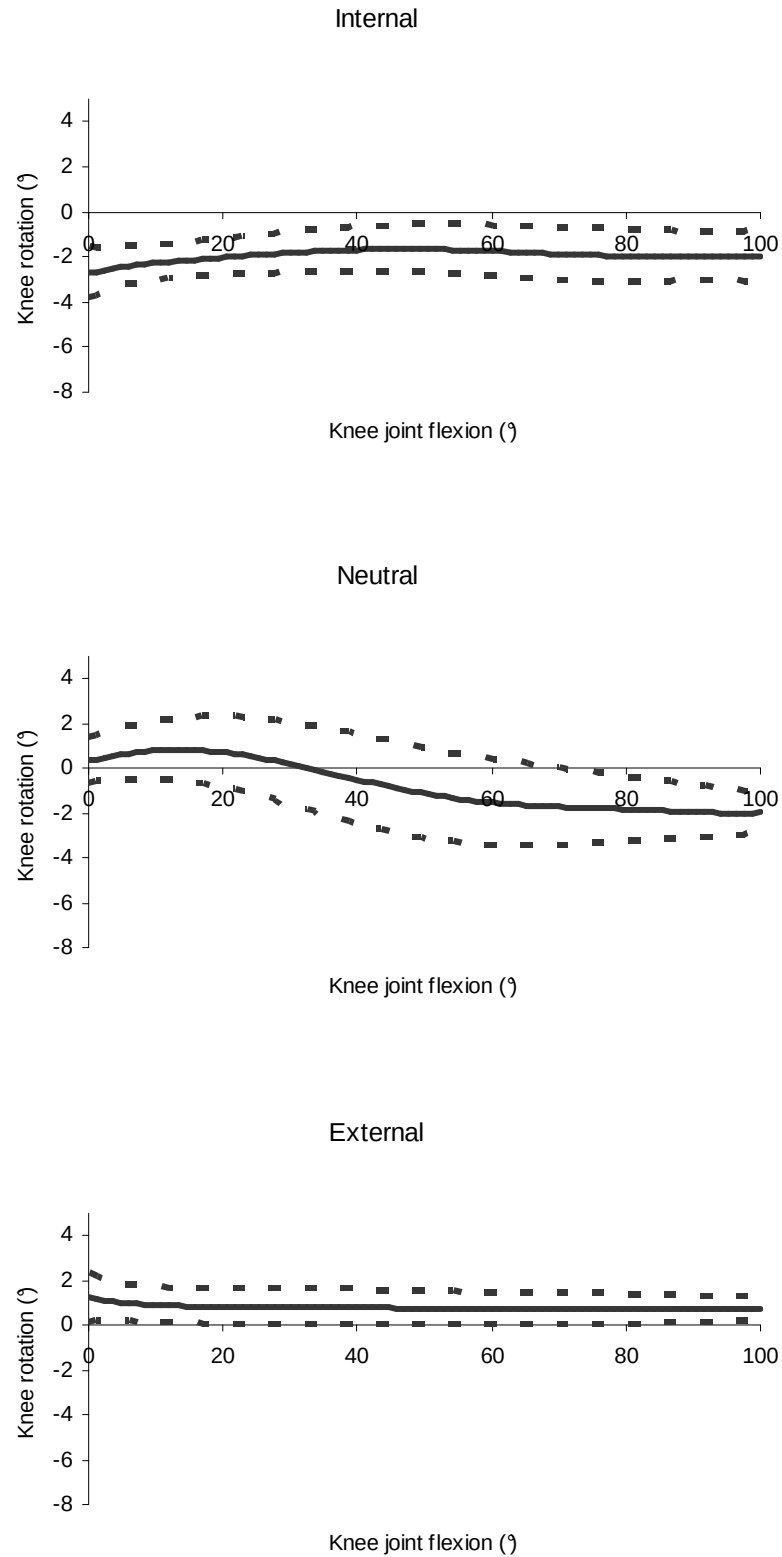


Figure 3.14: Mean changes in rotations after ACL section (continuous lines) and 95% confidence interval limits (dotted lines) without any drawer applied. Positive values mean external rotation, negative values internal rotation.

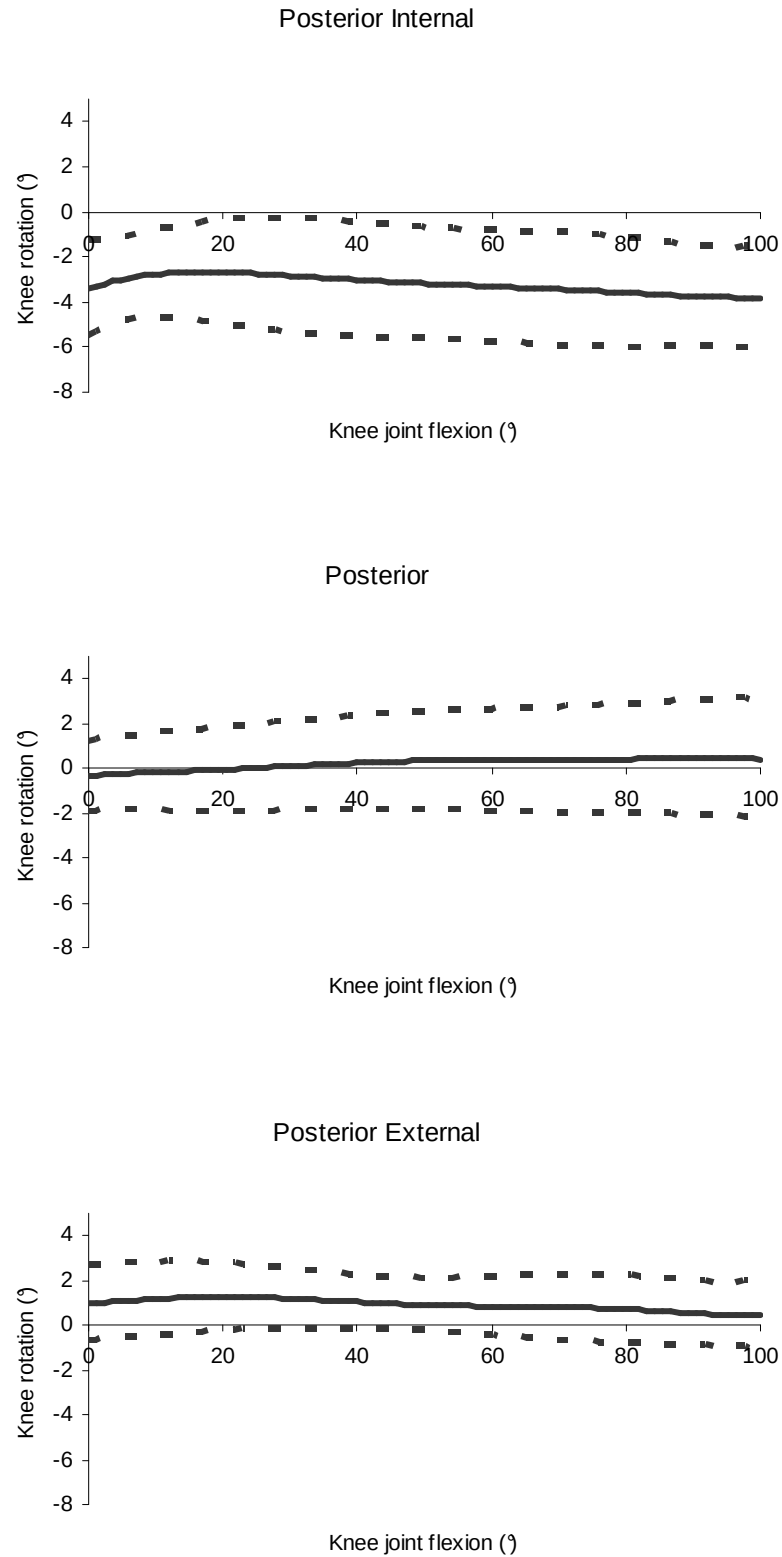


Figure 3.15 Mean changes in rotations after ACL section (continuous lines) and 95% confidence interval limits (dotted lines) under posterior drawer (90N) conditions. Positive values mean external rotation, negative values internal rotation.

3.1 Discussion

The principal finding of this study was that, while cutting the ACL had a statistically significant effect on tibial rotation laxity, these changes were not large enough to be detectable in the clinic. At the same time, it was found that imposing tibial rotations led to coupled anteroposterior translations of similar magnitude to those imposed directly by anteroposterior drawer forces. Although combinations of tibial drawer forces and rotations led to the largest changes in rotational laxity after ACL transection, these were still too small to be detectable clinically. Thus, the results did not support the initial hypothesis that combined loading, such as anterior drawer plus internal rotation, would yield useful information regarding the state of the ACL.

This study aimed to clarify the role of the ACL in controlling tibial rotational laxity by examining the effects of combined force plus torque loadings. It has long been accepted that the ACL is the primary restraint to tibial anterior translation (Amis, Dawkins 1991; Andriacchi, Dyrby 2005; Fukubayashi, Torzilli, Sherman et al 1982; Gollehon, Torzilli, Warren et al 1987; Haimes, Wroble, Grood et al 1994; Lane, Irby, Kaufman et al 1994; Lipke, Janecki, Nelson et al 1981), while its effect on rotation is debatable (Andriacchi, Dyrby 2005; Fukubayashi, Torzilli, Sherman et al 1982; Gollehon, Torzilli, Warren et al 1987; Haimes, Wroble, Grood et al 1994; Lane, Irby, Kaufman et al 1994; Lipke, Janecki, Nelson et al 1981; Markolf, Bargar, Shoemaker et al 1981; Nielsen, Helmig 1985; Reuben, Rovick, Schrage et al 1989; Seering, Piziali, Nagelet al 1980; Shoemaker, Markolf 1985; Bull, Andersen, Basso et al 1999; Kanamori, Zeminski, Rudy et al 2002; Leitzel, Losee, Jokl et al 2006), reflecting the small increases in rotational laxity resulting from isolated ACL deficiency. Being sited at the centre of the knee, it is to be expected that the ACL will be only a secondary restraint to tibial rotation, with the primary restraints at the periphery of the joint (Gollehon, Torzilli, Warren et al 1987; Haimes, Wroble, Grood et al 1994). Despite this observation, the clinical impression is that ACL injury results in knee instability that has at least a partly rotational component. In particular, the pivot-shift test has been shown to induce a combination of sudden anteroposterior translation and rotation of the tibia (Bull,

Andersen, Basso et al 1999). This was the stimulus for studying combinations of drawer forces and rotational torques in this study.

The application of combined loading conditions – drawer forces plus torques – did not lead to any greater clarity to help understand the effects of ACL deficiency. On the contrary, adding the extra loading conditions tended to reduce the laxities that were induced when each acted alone. These findings show that adding rotational effects will not help to diagnose ACL deficiency. Butler, Noyes and Groodl (1980) showed that the collateral ligaments share the load with the ACL, if they are tightened by tibial rotation: for example, tibial external rotation tightened the medial collateral ligament, reducing anterior translation laxity. Slocum and Larson (1968) used that observation as a basis for diagnosis of a combined injury, if the anterior drawer remained positive with the tibia held in a rotated position.

The largest anterior translation laxity for the intact knee was induced by an anterior drawer force – as expected – when the knee was flexed more than 45°, but tibial external rotation also induced anterior translation near extension (Fig. 3.8). This coupled anterior translation of the centre of the tibial plateau suggests that, with the leg hanging from the knee, the medial compartment had moved anteriorly more than the lateral compartment moved posteriorly. The finding that an isolated tibial external rotation induced an anterior drawer may relate to the mechanism of non-contact ACL injuries, if the foot is fixed to the ground and the knee is forced into external rotation.

The diagnosis of ACL injury by physical examination depends on identification of abnormal increases in tibiofemoral laxity, and Figure 3.9 shows that the largest change occurred around 20-30° of flexion, in response to an anterior drawer force. This confirms the efficacy of the Lachman test for the diagnosis of isolated ACL injury (Torg, Conrad, Kalen 1976). The small changes of rotational laxity after ACL transection, with any loading combination (Figure 3.13, 3.14, 3.15) implies that abnormal rotational laxity after an ACL injury has resulted from damage to other structures around the periphery of the knee.

If the tibia is displaced anteriorly or posteriorly, the resulting translation is accompanied by a tibial coupled rotation. Figure 3.9 shows that the anterior drawer (A) had induced a coupled internal rotation, and vice versa for posterior drawer. This suggests greater mobility for the lateral compartment in anteroposterior drawer testing. Figure 3.13 shows that cutting the ACL did not alter this effect, suggesting that coupled rotations are induced or controlled by the peripheral structures. The magnitude of coupled rotations will depend on the freedom of rotation of the tibia and the magnitude and line of action of the drawer force. Although these coupled rotations are quite small ($2-3^{\circ}$ in response to 90N drawer force in this study; 6° in response to 125N drawer force in Gollehon, Torzilli, Warren(1987), 9° in response to 150N in Amis and Scammell(1993)), Piziali, Rastegar, Nagel et al(1980) showed that inhibiting coupled rotations reduced anteroposterior laxity approximately 30%.

In this study the employed anterior force (90N) was deliberately inferior than in previous investigations (125N in Gollehon, Torzilli, Warren 1987; 150N in Amis and Scammell 1993). An inferior force, besides avoiding to recruit peripheral structures, shouldn't cause irreversible material stretching particularly at the time of reconstruction (Chapter 4 and 5) when a tendinous graft is employed to replace the native ligament or its bundles. Furthermore a 90N force is very close to the 89N force applied to the tibia in the clinical setup with KT- arthrometers to test ACL function (Daniel, Malcom, Losse et al 1985)

Cutting the ACL caused a significant change in the "neutral" resting position of the tibia in relation to the femur. Figure 3.11 shows that the tibia moved anteriorly, by approximately 4 mm at 20° of flexion, reducing to 2mm at 90° of flexion. Although Figure 3.13 shows that the tibial anterior shift was accompanied by a significant tibial internal rotation in the flexed knee, the magnitude of this change (approximately 2°) would not be clinically detectable. The effect of this shift of the resting position of the tibia, after ACL injury, is to reduce the movement that would be induced by an anterior drawer test. Figure 3.11, that shows the changes caused by ACL transection, shows that failure to account for the change in the neutral (N) condition would have reduced the apparent effect of loss of the ACL on anterior drawer (A) by nearly 50%. In order to avoid this effect, it is

recommended that side-to-side differences are measured from a posteriorly-reduced position if the PCL is intact.

The results of this study must be interpreted in the light of the limitations imposed by working in-vitro. The experimental set-up, in which the leg hangs vertically below the knee while the femur is flexed-extended above it, has already been used in a similar work (Grood, Stowers, Noyes 1988). It has the advantage that known displacing loads can be applied to the quasi-stationary tibia and is akin to examining the knee of a live patient sitting on the bed with the feet dangling over the edge. The lack of joint loading creates a specific condition, that only relates to examination of a completely relaxed knee. Compressive loading reduces the anteroposterior laxity of the knee (Shoemaker, Markolf 1985), tending to locate the medial femoral condyle into the concavity of the medial tibial plateau. Similarly, the pivot shift test compresses the lateral compartment by imposing a valgus moment across the knee (Bull, Andersen, Basso et al 1999). It is possible that that would alter the small response seen in this work to the combined anterior drawer plus internal rotation loading.

This study has not found responses to combined tibial drawer force plus rotation torque loading that would add new information in clinical diagnosis of ACL injury. However, it has demonstrated coupled rotation-translation effect, especially the tibial anterior translation that accompanied external rotation; that may relate to non-contact ACL injury. The small changes to tibial rotation that followed isolated ACL transection suggest that abnormalities of tibial rotation laxity seen clinically relate to the peripheral structures being damaged.

Chapter 4 – ACL Bundles Contribution to Knee Laxity

In Chapter 3a method to experimentally assess intact knee laxity through the use of combined loading to obtain an envelope of laxity or kinematics was developed and validated. Then the effects of cutting the ACL on the envelope were tested. This resulted in the assessment that the ACL is a primary restraint to anterior tibial translation and tibial internal rotation. In this chapter the effects of cutting the separate ACL bundles on the envelope of laxity will be tested.

4.1 Introduction

The ACL is a primary restraint against tibial anterior translation, contributes to the control of knee rotations and avoids the pivot shift phenomenon (Amis, Dawkins 1991; Bull, Andersen, Basso et al 1999; Butler, Noyes, Grood 1980; Fukubayashi, Torzilli, Sherman et al 1982). These properties are the result of the ACL's complex multifascicular structure, which is a continuum of variously oriented collagen fascicles that are recruited differently when external loads are applied. As demonstrated in Chapter 3, two main functional bundles of fascicles can always be identified within the ACL: the AMB and the PLB (Chapter 3). The PLB is shorter, has a more distal/posterior attachment on the femur and is taut exclusively in extension; the AMB on the contrary is longer, has a more proximal/anterior femoral attachment and is taut throughout the range of knee flexion-extension (Zantop, Petersen, Sekiya et al 2006; Zantop, Herbort, Raschke et al 2007).

Although the different recruitment of the two bundles across the range of knee flexion-extension has been described by observational and more sophisticated studies (Norwood, Cross 1979; Bach, Hull Patterson 1997, Gabriel, Wong, Woo et al 2004), there is no evidence in the published literature of any assessment of the contribution of each of the bundles to controlling both the translational and rotational laxity of the knee, apart from Amis and Dawkins (1991) who documented a tension increase in the bundles when they withstood an anterior force or an internal rotation torque. The purpose of this study was to assess the changes in anteroposterior (AP) and rotational knee laxity after selective cutting of each bundle. This should 1) improve the knowledge of the function of the native ACL, 2) help to recognise the laxity pattern of partial ACL tears and 3) contribute to understanding whether the reconstruction of both ACL bundles is needed after a complete ACL injury to restore intact knee laxity.

4.2 *Material and Methods*

Fourteen fresh frozen cadaver knees from consented donors (mean age: 64.5 years old; range 48-74) were obtained from a tissue bank (IIAM, Jessup, PA) in conformity with a local Research Ethics Committee permit, thawed overnight, and prepared in the same way as in Chapter 3.

The limits of tibial AP translation and internal-external rotation were recorded from 0° to 100° knee flexion under the application of a 90N anterior or posterior force and a 5Nm internal or external rotation torque, respectively.

The recordings were obtained in the intact knee and after alternate selective cutting of the AMB or PLB (Fig. 4.1). The AMB and PLB were identified and separated with the knee at 90° of flexion under the application of a 90N tibial anterior force which tightened the AMB and left the PLB relaxed.

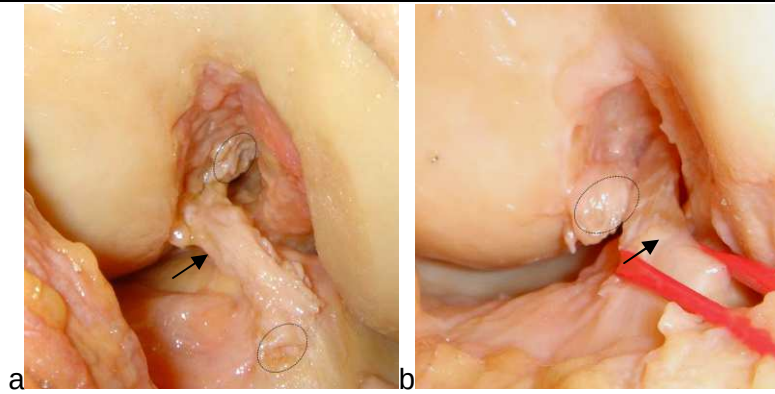


Figure 4.1: a) AMB cut and PLB (arrow) left intact; b) PLB cut and AMB (arrow) left intact

The deficient bundle was then reconstructed with a 6mm bovine extensor tendon graft passed through bony tunnels on the tibia and femur which exited in the native bundle attachments (Fig. 4.2). The elastic properties of bovine extensor tendons do not differ significantly from human hamstrings tendons (Donahue, Gregersen, Hull 2001)

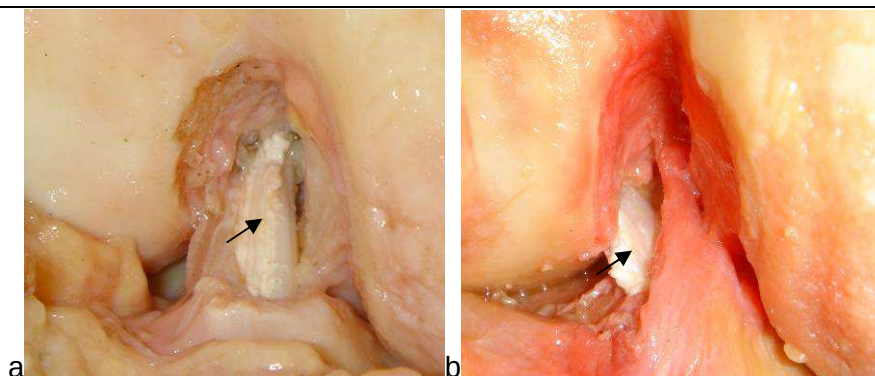


Figure 4.2: isolated AMB (a) and PLB (b) reconstruction with bovine grafts (arrows)

The grafts were looped over a Kirschner wire on the femur at the tunnel exit and the free ends exited from the tibial tunnels and were attached through polyethylene sutures to a load cell which was secured on the tibial rod (Fig. 4.3). AMB and PLB graft tensions were adjusted to match intact knee antero-posterior position at 90° and 20° of flexion respectively. If intact knee laxity was already matched a 5N tension was applied to the graft. After the reconstruction, the limits of anterior translation and internal rotation were measured.

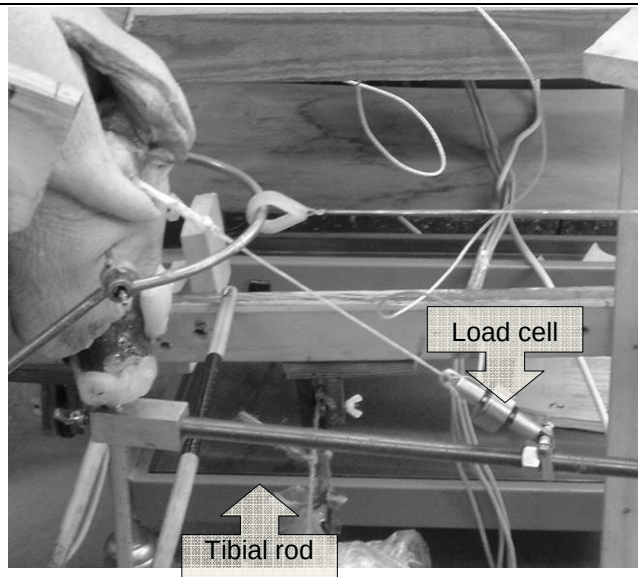


Figure 4.3: a load cell secured to tibial rod measured tension changes in the graft

Continuous data were interpolated to single degree of flexion increments and analysed using SPSS 13.0 for Windows (SPSS Inc., 1989-2004). Tibial rotations and translations for each loading condition were compared to the AP and rotational position of the intact knee in the neutral condition without external loads at each degree of knee flexion. Mean differences and 95% confidence intervals of the differences in translations and rotations between the different knee conditions were calculated at single degree of flexion increments and plotted. In the same way as for Chapter 3 it was assumed, according to the sign test, that when the confidence interval of a difference did not change sign, then the difference was statistically significant ($p < 0.05$).

4.3 Results

One knee was excluded for abnormal varus-valgus laxity in extension. This was defined as a laxity of greater than 5° . In one knee in which the AMB was cut first, the PLB broke when the 90N anterior force was applied, so data from twelve knees were available and are presented here.

Changes in anterior translation limit

When the AMB was cut first there was a significant increase in tibial anterior translation laxity throughout the range of knee flexion. It increased further when the PLB was also sectioned. From 40° of flexion onward the tibial anterior translation laxity with the AMB cut did not differ significantly from that recorded after the complete section of the ACL (Fig. 4.4).

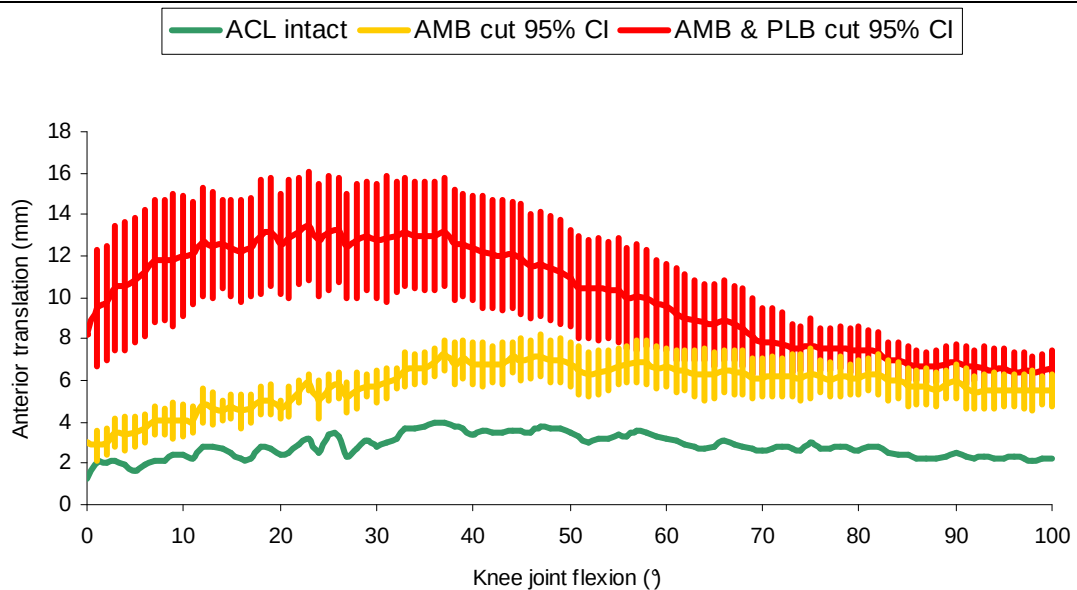


Figure 4.4: Changes in anterior translation after isolated AMB section or complete ACL section. According to the sign test, when the confidence interval of a difference does not change sign, then the difference is statistically significant ($p < 0.05$)

When the PLB was cut first no significant changes in tibial anterior translation were recorded throughout the range of knee flexion. Cutting the AMB then caused a significant increase in tibial anterior laxity at all angles of flexion (Fig. 4.5).

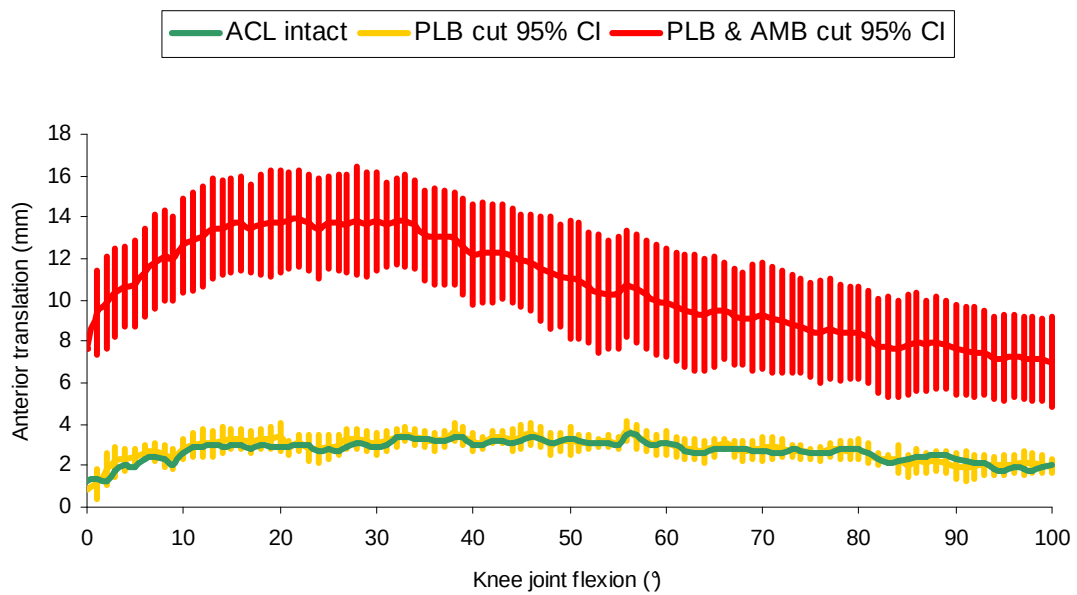


Figure 4.5: Changes in anterior translation after isolated PLB or complete ACL section.

Changes in internal rotation limit

Isolated section of the AMB did not affect the limit of internal rotation significantly with knee flexion apart from 0° to 30° when a slight increase (in the order of 1°) of internal rotation could be recorded (Fig. 4.6).

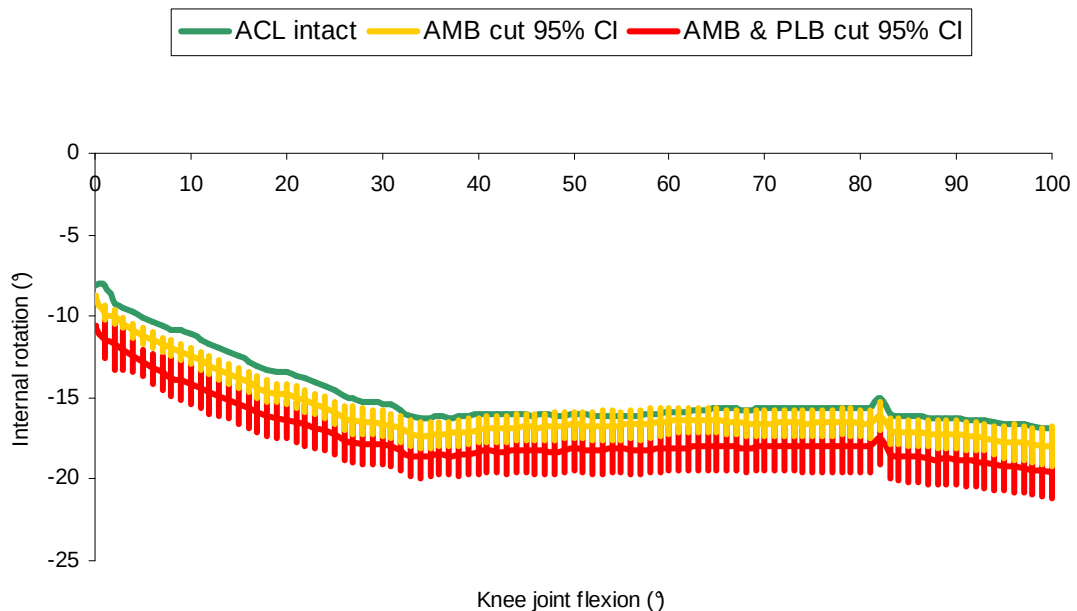


Figure 4.6: Changes in internal rotation after isolated AMB or complete ACL section.

The isolated section of the PLB resulted in small but statistically significant changes in internal rotation laxity (Fig. 4.7). The complete section of the ACL caused a slight, though statistically significant, increase of the internal rotation limit, particularly close to extension (Figs. 4.6 and 4.7).

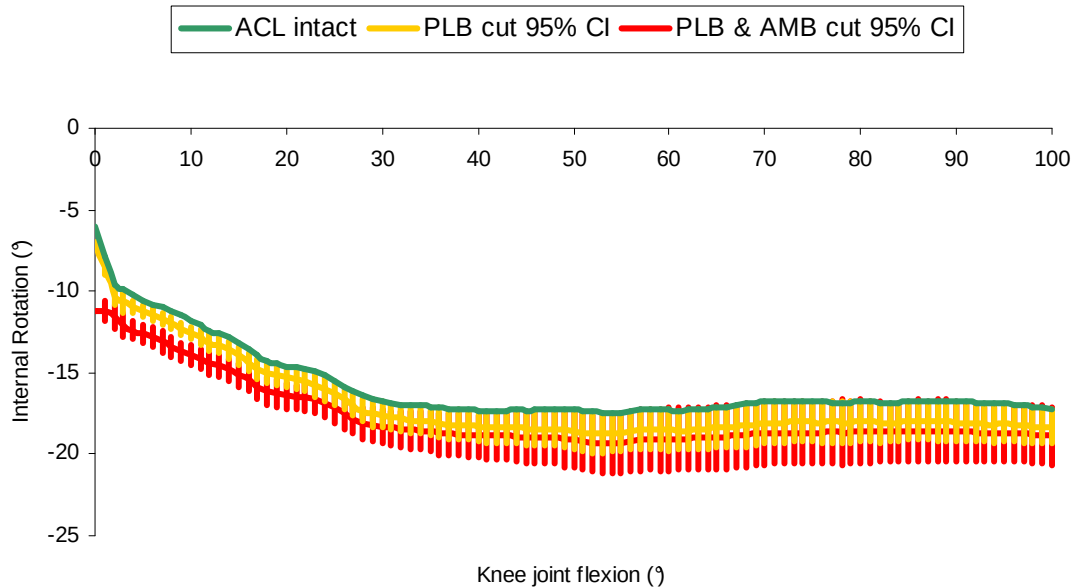


Figure 4.7: Changes in internal rotation after isolated PLB or complete ACL section.

Isolated bundle reconstruction

The tension required in the AMB and PLB graft to match intact knee laxity was $20\text{N} \pm 8(10-35)$ (mean $\pm$ 1SD, range) and $16\text{ N} \pm 14(5-40)$ respectively. Figure 4.8 shows tension changes in the grafts: the AMB had a smaller tension change through flexion-extension with a gradual increase from flexion to extension; on the other hand the mean PLB tension rose from 30° to 0° .

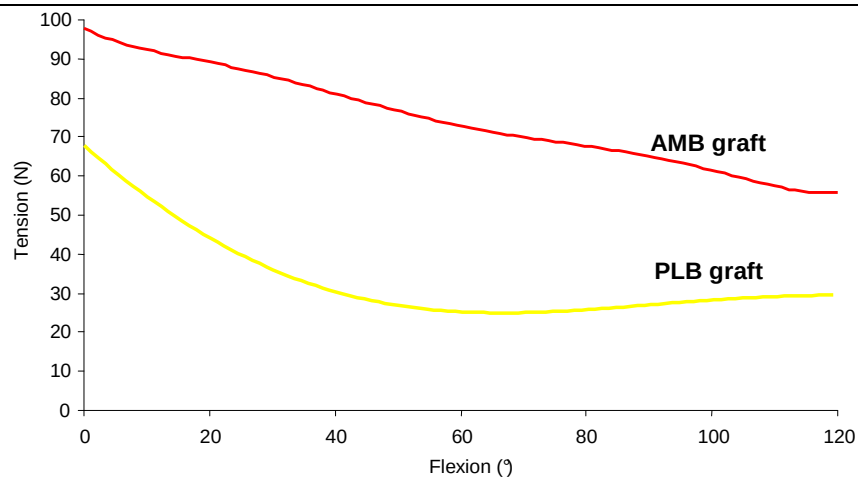


Figure 4.8: tension changes in AMB (red) and PLB (yellow) graft after reconstruction

The reconstruction of the AMB restored intact knee laxity (Figs. 4.9 and 4.10).

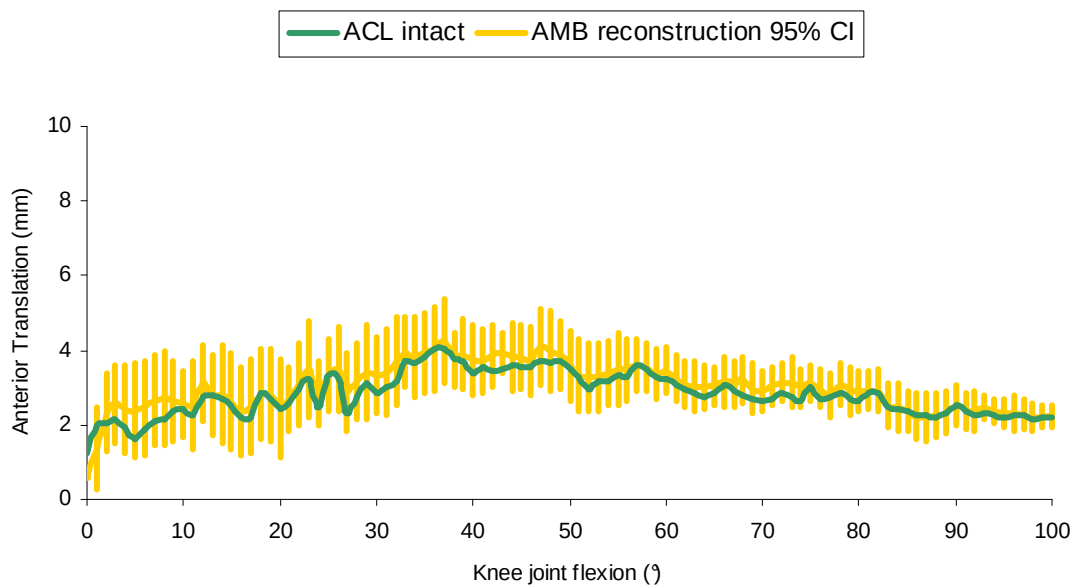


Figure 4.9: intact knee anterior translation limit restored after AMB reconstruction

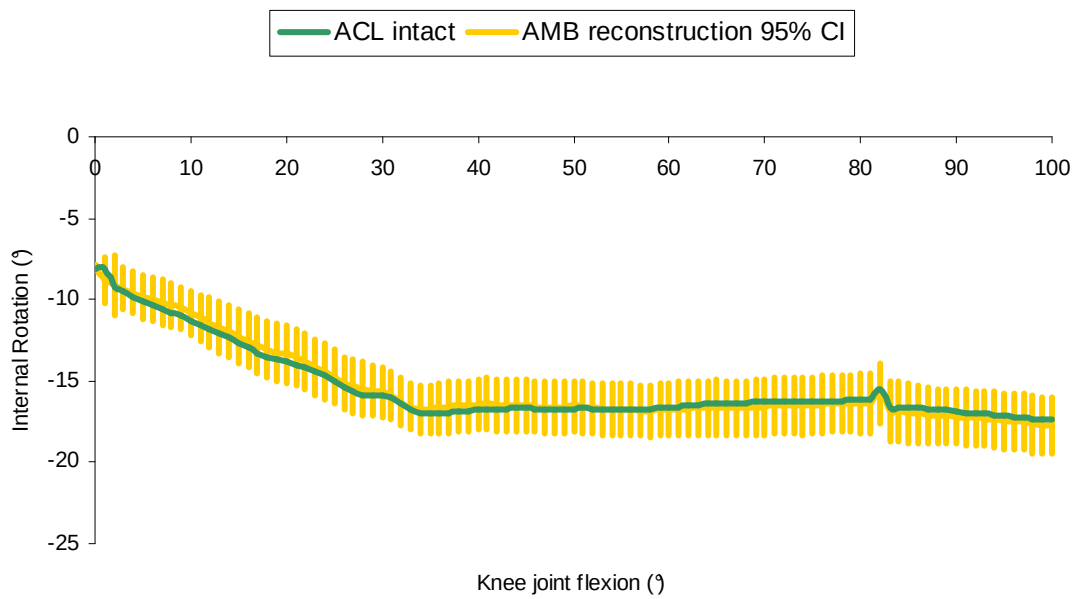


Figure 4.10: intact knee internal rotation limit restored after AMB reconstruction

Figures 4.11 and 4.12 show how intact knee anterior translation and internal rotation are restored after isolated PLB reconstruction.

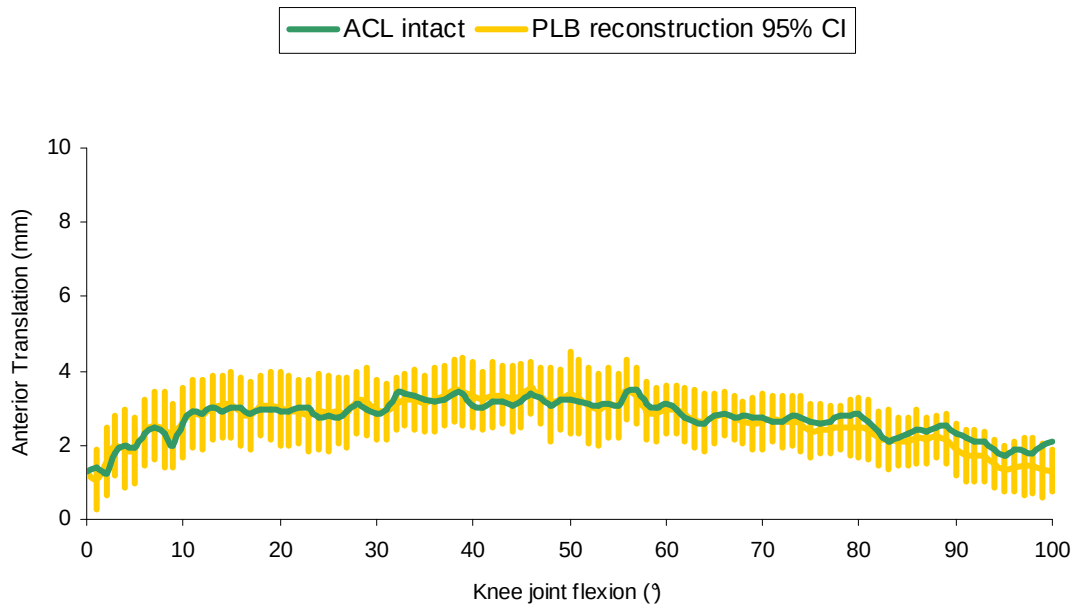


Figure 4.11: isolated PLB reconstruction effects on anterior translation limit

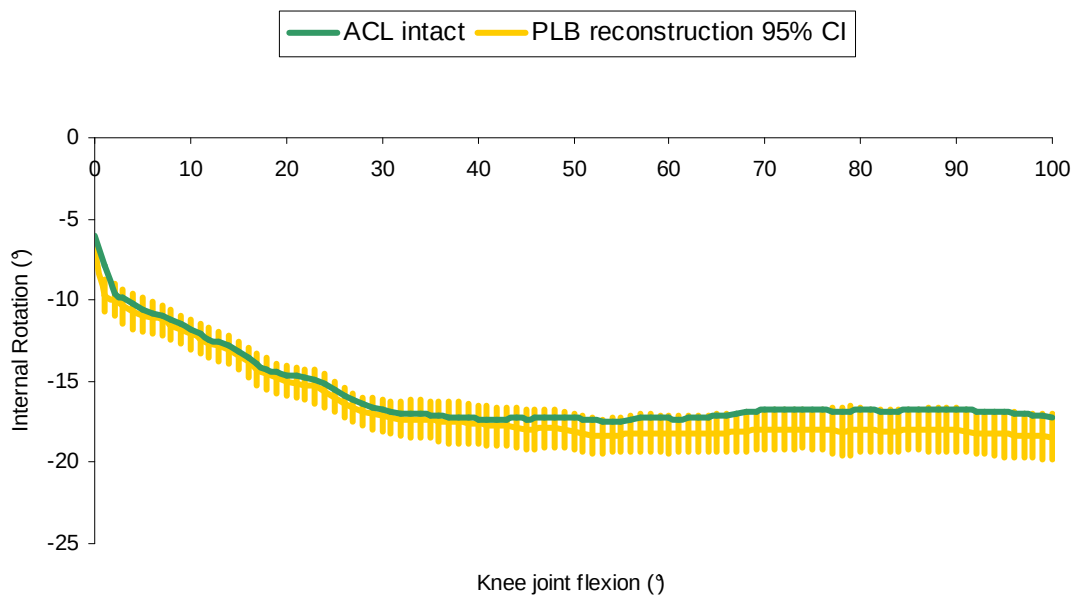


Figure 4.12: isolated PLB reconstruction effects on internal rotation limit

4.4 Discussion

The main finding of this investigation is that the two ACL bundles have different functions: the AMB is the primary restraint against tibial anterior translation and both of them control rotation, although the section of the entire ACL results only in minimal internal rotation increase. These findings have been hypothesized by other authors (Zantop, Petersen, Sekiya et al 2006; Zantop, Herbolt, Raschke et al 2007) but up to now were speculative.

The AMB alone is able to withstand anterior translation (drawer) forces (at least up to 90N) and the limit of tibial anterior translation does not change significantly after the PLB has been cut, from 0° to 100° knee flexion (Fig. 4.5).

The PLB is a secondary restraint to tibial anterior translation in extension: it allows only a few millimetres increase of tibial anterior translation after the section of the AMB (Fig. 4.6), which then increases substantially when the PLB is also cut, from 0° to 40° knee flexion. From 40° of flexion onward the PLB has no effect

on anterior translation limit which is controlled exclusively by the AMB. This reflects the slackening of the PLB in flexion.

Both bundles contribute to control internal rotation apparently in the same amount (Figs. 4.7 and 4.8).

A main limitation of this study is the relatively low loads employed. Other authors applied higher loads to the knee when they investigated the function of the entire ACL (Fukubayashi, Torzilli PA, Sherman et al 1982). In this study, lower loads were applied deliberately not to recruit peripheral ligamentous and capsular structures which would act as secondary restraints to knee translations and rotations. Furthermore it was hypothesised that isolated bundles can withstand lower loads than the entire native ACL. As a matter of fact in one knee the PLB left alone broke under the action of a 90N anterior force.

The findings of this study may provide the rationale to better understand partial ACL tears and maybe predict them on the basis of the clinical laxity changes. Though partial ACL tears are still not well defined, several papers have been published in this field (Buckley, Barrack, Alexander 1989; Duri, Aichroth 1995, Noyes, Mooar, Moorman et al 1989, Siebold, Fu 2008) Furthermore it is not uncommon in clinical practice to examine patients who sustained an injury, complain of little or vague instability and have only either a Grade 1 Lachman sign or a Pivot Shift glide; further arthroscopic evaluation often shows a tear involving only one part of the ACL while the rest is still intact.

Most authors have classified partial tears as percentage of the involved ACL. Duri and Aichroth (1995) on the contrary followed an anatomical criterion and reported on 35 patients with an acute partial ACL tear who had only a Lachman grade 1 or less (63% of the patients) or a pivot shift glide (10%). 14 knees were scoped and an isolated tear of the PLB was observed in 36% of the knees while in 50% of the knees the ACL “did not rise to the summit of the intercondylar notch in the usual way but diverted posteriorly to the capsule below its usual attachment”. The latter description suggests that the AMB femoral attachment was involved.

Though the mechanism of injury which would lead to the tear of only one of the ACL bundles is not clear yet, on the basis of our findings some hypotheses can

be formulated to predict the pattern of ACL lesion on the basis of the clinical instability. If only a Grade 1 Lachman test and an absent pivot shift are recorded a lesion involving mainly the AMB can be hypothesised; vice versa if a Pivot Shift glide is present without any increase in anterior tibial translation a tear involving mainly the PLB could be suspected. Unfortunately none of the clinical studies on partial ACL tears tried to correlate the clinical signs to the pathology. It is known, though, that the AMB remains relatively tight across the range of knee flexion, while the PLB is slackened in flexion and tightened rapidly by full knee extension (Amis, Dawkins 1991). Thus, the PLB may be vulnerable to hyperextension injuries and the AMB must take all the load in flexion.

Even if these observations can help to clinically identify isolated bundle lesions it must be emphasized that these entities are not common, more frequently observed in the acute phase and are destined to become complete ACL tears (Noyes, Mooar, Moorman 1989). Half an ACL in fact cannot withstand the same loads of the native ligament as demonstrated also by the failure of one residual PLB that was observed after the application of a 90N anterior translation force. Anyway if a partial tear is suddenly recognised and diagnosed the reconstruction of the torn bundle can restore intact knee laxity (Figs. 4.9 - 4.12)

The results of this investigation support the reconstruction of both the AMB and PLB in complete ACL tears. Conventional single bundle ACL reconstruction which usually replicates mainly the AMB is believed by some authors to be not enough to restore intact knee stability. In particular a significant incidence of residual positive Pivot Shift sign has been reported (Aglietti, Giron, Buzzi et al 2004; Bull, Earnshaw, Smith et al 2002; Lie, Bull, Amis 2007). It can then be hypothesized that this results from the absence of the PLB, which helps to control rotations. It seems evident after this investigation that the two bundles have a load sharing behaviour after a rotational torque.

Although a positive Pivot Shift is pathognomonic of ACL insufficiency and is the result of combined abnormal rotations and translations (Bull, Andersen, Basso et al 1999), in these experiments a large increase in internal rotation was not found. In this light the Pivot Shift phenomenon needs a better understanding with

respect to the limits of pure tibial internal rotation. The contributions of the bundles of the ACL to pivot shift control would then need to be investigated.

Based on the above findings, in the following chapter a study is presented which tests whether the reconstruction of both ACL bundles is effective in restoring intact knee laxity compared to traditional single bundle reconstruction.

Chapter 5 – Double Bundle ACL Reconstruction

In Chapter 4 the contribution of the AMB and PLB of the ACL to control intact knee laxity was investigated and the importance of both bundles in controlling the limits on anterior translation and internal rotation was demonstrated. In this chapter the efficacy of reconstructing both ACL bundles in controlling knee laxity will be tested and compared to conventional single bundle reconstruction.

5.1 Introduction

Double bundle (DB) ACL reconstruction is being introduced to clinical use and this is supported by scientific evidence that the replication of both the AMB and the PLB of the native ligament ensures a better control of anteroposterior and rotational laxity than traditional single bundle (SB) procedures (Radford, Amis 1990; Yagi, Wong, Kanamori et al 2002). Furthermore, although early clinical experiences (Adachi, Ochi, Uchio et al 2004; Muneta, Sekiya, Yagishita et al 1999) did not show a clear advantage with DB techniques, more recent series have demonstrated some advantage, at least at short term follow-up (Muneta, Koga, Morito et al 2006; Yasuda, Kondo, Ichiyama et al 2006; Mae T, Shino K, Matsumoto et al 2010; Yasuda, Tanabe, Kondo et al 2010; Muneta, Koga, Mochizuki et al 2007; Fu, Shen, Starman et al 2008; Song EK, Oh LS, Gill et al 2009; Järvelä, Moisala, Sihvonen et al 2008).

Despite recent anatomical studies on native bundle attachments (Giron, Cuomo, Aglietti et al 2006; Mochizuki, Muneta, Nagase et al 2006; Takahashi, Doi, Abe et al 2006; Zantop, Petersen, Sekiya et al 2006) which should improve tunnel

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positioning, no consensus exists on how best to tension DB grafts (Miura, Woo, Brinkley et al 2006; Chen, Gadikota, Gill et al 2010). Proper graft tensioning is critical for restoring normal AP laxity in SB reconstructions (Amis, Jakob 1998) and should influence DB procedures as well. With two independent intra-articular bundles replicating the native ACL, load sharing should be expected. However stress shielding of one bundle might occur if the other is too tight. Similarly the combined effect of two tight bundles with possible subsequent overconstraint of the joint might also be anticipated.

This investigation was set up to test the effects of different DB graft tensioning strategies with appropriate anatomical graft positioning, on knee laxity and bundle tension. The aim was to identify the best protocol for restoring normal patterns of knee laxity. It was hypothesized that the sequence of tensioning the grafts at different angles of knee flexion should affect both knee laxity and graft tension.

5.2 Materials and Methods

Seventeen fresh-frozen cadaver knees from consented donations (mean age: 64.5 years old; range 48-74) were obtained from a tissue bank (IIAM, Jessup, PA, USA) in conformity with a Local Research Ethics Committee permit and related legal requirements and prepared in the same way as in Chapter 3.

The limits of tibial AP translation and internal-external rotation were recorded from 0° to 100° knee flexion under the application of a 90N anterior or posterior force and a 5Nm internal or external rotation torque, respectively.

After recording intact knee laxity the AMB and PLB were isolated and separated as described in Chapter 4. The bundles were cut in their midsubstance, their tibial and femoral attachments demarcated and ACL deficient limits of tibial motion recorded.

A 6 mm outside-in tunnel was drilled in the centre of each bundle attachment with a commercially available point and shoot guide (Arthrex Inc, FL, USA). Size-

specific double-stranded pretensioned bovine extensor tendon grafts were lubricated with synthetic grease to reduce friction and passed through the tibial and femoral tunnels to reconstruct both bundles (Fig. 5.1).

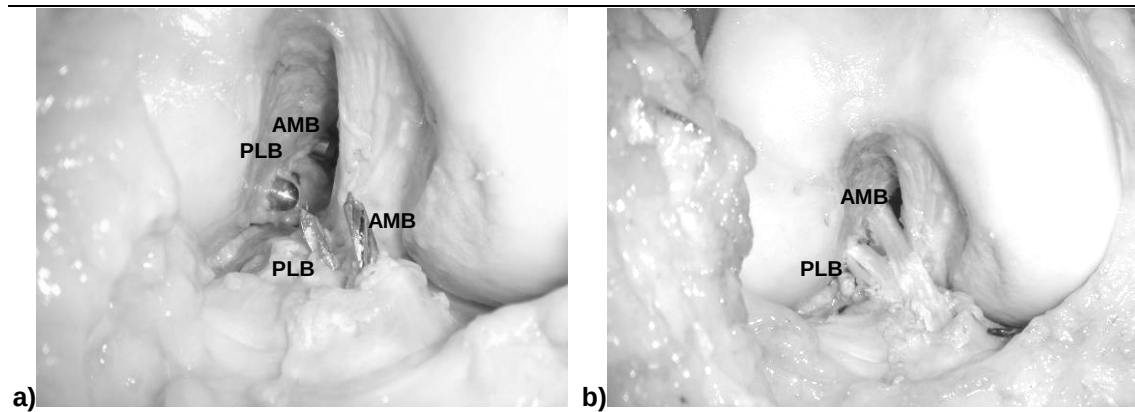


**Figure 5.1: a) AMB and PLB tunnel exits in the centre on the native bundle attachment;
b) AMB and PLB bovine grafts**

For the proximal fixation, the grafts were looped over a 3 mm K-wire fixed rigidly to the femoral cortex across the tunnel entrances. The free ends of the grafts exited the tibial tunnels and were connected with stiff #2 Ultrabraid sutures (Smith&Nephew, Inc, Andover, MA, USA) to two load cells (Entran Sensors & Electronics, Fairfield, NJ, USA) which had been secured previously to the tibial intramedullary rod via two perpendicular threaded bars which allowed the load cells to be adjusted coaxial with the tibial tunnels (Fig. 5.2).

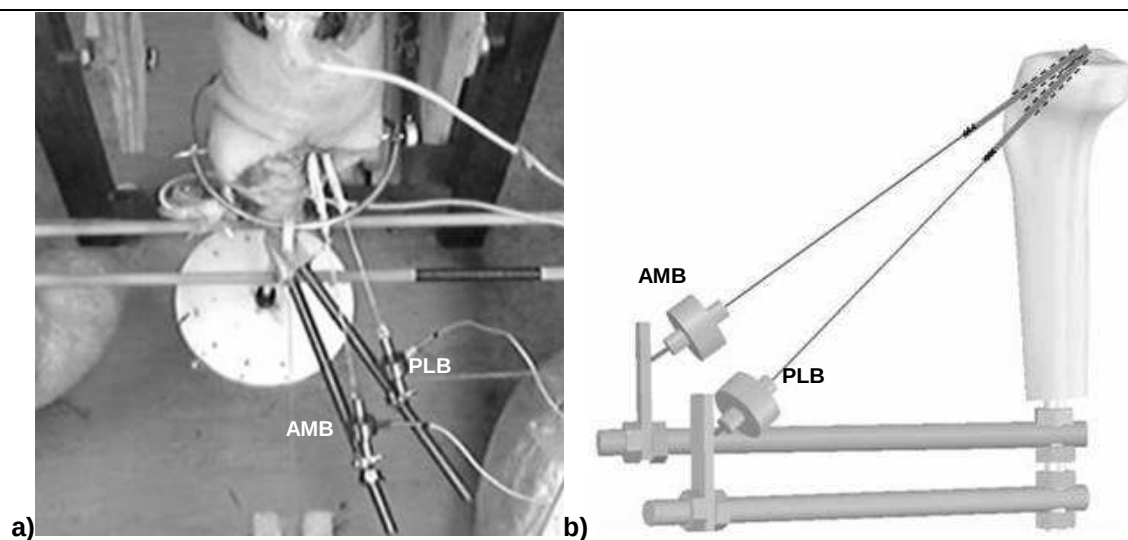


Figure 5.2: a) tibial AMB and PLB graft fixation to two load cells which are rigidly secured to tibia via non ferromagnetic rods (b)

Under a 40N tibial posterior drawer force, which resembled the action of the weight of the leg at the moment of fixation during surgery, tension in each graft was increased incrementally and the resulting anterior translation laxity measured with the 90N drawer force. If it did not match the laxity of the intact knee, the tension was adjusted while the knee again had 40N posterior drawer, and the anterior laxity re-measured, until it matched the intact state within $\pm 0.5\text{mm}$. Anteroposterior and rotational laxity resulting from the loads described above, as well as graft tension changes, were then recorded across the range of knee flexion-extension after 3 tensioning strategies: 1) AMB graft tensioned first at 90° of flexion and then PLB at 20° ; 2) PLB tensioned first at 20° and then AMB at 90° ; 3) both bundles tensioned together at 20° .

After completing the recordings the 4 tunnels were filled with polyester resin (ABL Stevens Resin & Glass, Ltd - Sandbach UK). After the resin became hard, single tibial and femoral 8 mm tunnels were drilled in the centres of the native ACL attachments at the junction between the two bundles. A size-specific pretensioned double-stranded bovine extensor tendon graft was passed into the joint (Fig. 5.3). Opening up of the holes through the resin was not observed as well as graft slippage. SB graft was fixed and tensioned in the same fashion as the double-bundle grafts, to match the anterior laxity of the intact knee at 20° of knee flexion. The envelopes of laxity were measured again, as described above.

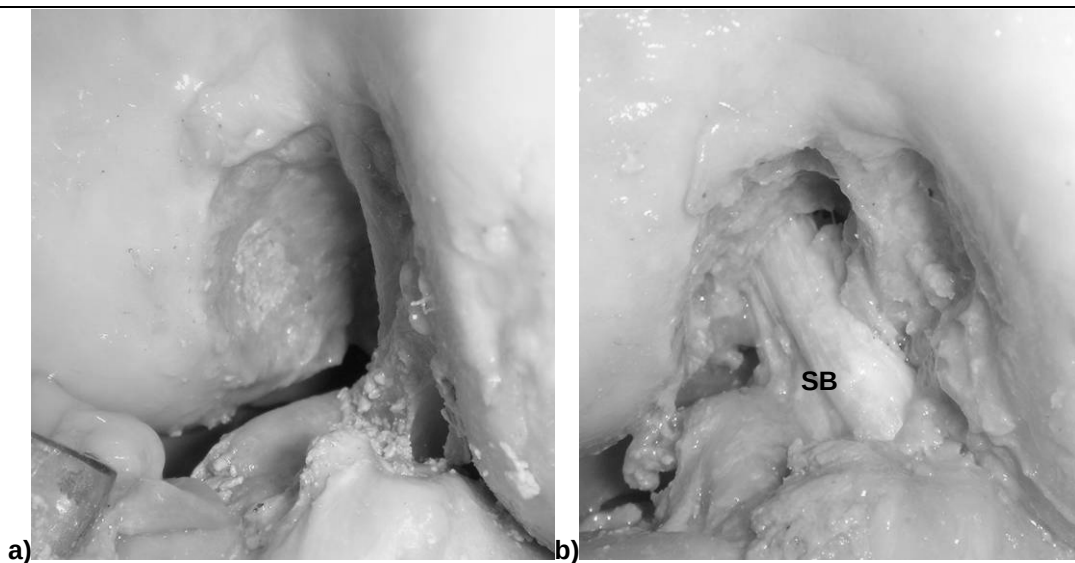


Figure 5.3: a) DB reconstruction tunnels filled with resin; b) SB reconstruction

The entire experimental procedure took about one hour per knee to be completed. During the preparation and the tests the specimen and soft tissue graft were kept moist with saline solution.

Continuous kinematics and tension data were linearly interpolated to single degree of flexion increments and analysed using SPSS 13.0 for Windows (SPSS Inc., 1989-2004). Tibial rotations and translations from each loading condition were normalised to the anteroposterior and rotational position of the intact knee in the neutral condition without external loads at each degree of knee flexion. Mean differences and 95% confidence intervals of the differences in translations and rotations between the different knee conditions and intact knee envelope of laxity were calculated at single degree of flexion increments and plotted. It was assumed, according to the sign test, that when the confidence interval of a difference did not change sign, then the difference was statistically significant ($p < 0.05$).

5.3 Results

ACL transection resulted in a significant tibial anterior translation throughout the range of motion and slight but significant tibial internal rotation as observed in Chapter 3.

The highest tension to match intact knee anterior laxity was required when the PLB was tensioned first : 43 ± 29 N in the PL graft and 60 N total tension (Table 5.1). The other reconstructions all required a similar total tension in order to match the intact knee laxity: 37 N for AM graft tensed first; 34 N for both DB grafts tensed together; 38 N for the SB graft. Table 5.1 also shows large standard deviations on the mean PLB-first and SB graft tensions, so some knees required large graft tensions in order to restore anterior laxity to the intact values.

	Tension (N) in AMB	Tension (N) in PLB
DB AMB 1st	19 ± 4 (11-25)	18 ± 27 (5-24)
DB PLB 1st	17 ± 20 (5-37)	43 [§] ± 29 (27-58)
DB together	17 ± 11 (9-28)	17 ± 11 (9-28)
SB	38 ± 27 (19-55)	

Table 5.1: graft tension required with a 40N tibial posterior force to match intact knee laxity with 90N anterior drawer force applied (mean +/- SD, n=14); [§]: significantly different from DB AMB 1st and DB together (p<0.05 after Bonferroni adjustment).

Tension patterns in the flexing knee with an anterior drawer force were not affected by the tensioning strategy: PLB grafts always showed the largest variation in tension with peak values at full extension. The tension in the AMB graft changed less across the range of motion, with a peak around 30° knee joint flexion (Tab. 5.2).

	Max. Tension (N) in AMB (Flexion angle)	Max. Tension (N) in PLB (Flexion angle)
DB AMB 1st	80 [§] ± 23 (22° ± 24°)	41 ± 33 (0° ± 0°)
DB PLB 1st	55 ± 25 (31° ± 28°)	85* ± 26 (0° ± 3°)
DB together	63 ± 13 (23° ± 18°)	64 ± 13 (0° ± 0°)
SB	127 ± 47 (0° ± 0°)	

Table 5.2: maximum graft tension and angle of knee flexion angle at which it was recorded with a 90N anterior drawer force applied (mean ± SD, n=14); [§]: significantly different from DB PLB 1st (p<0.05 after Bonferroni adjustment); *: significantly different from DB AMB 1st and DB together (p<0.05 after Bonferroni adjustment)

Overall tension values, on the contrary, were affected by the tensioning strategy. In DB reconstructions the graft which was tensioned first recorded the highest tension values, particularly the PLB graft. The lowest tension under an anterior force was recorded when both bundles were fixed together (Table 5.2 - Fig 5.4).

With an internal rotation torque the tension in the grafts tended to be less than under an anterior drawer force, particularly the AMB graft (Fig. 5.5).

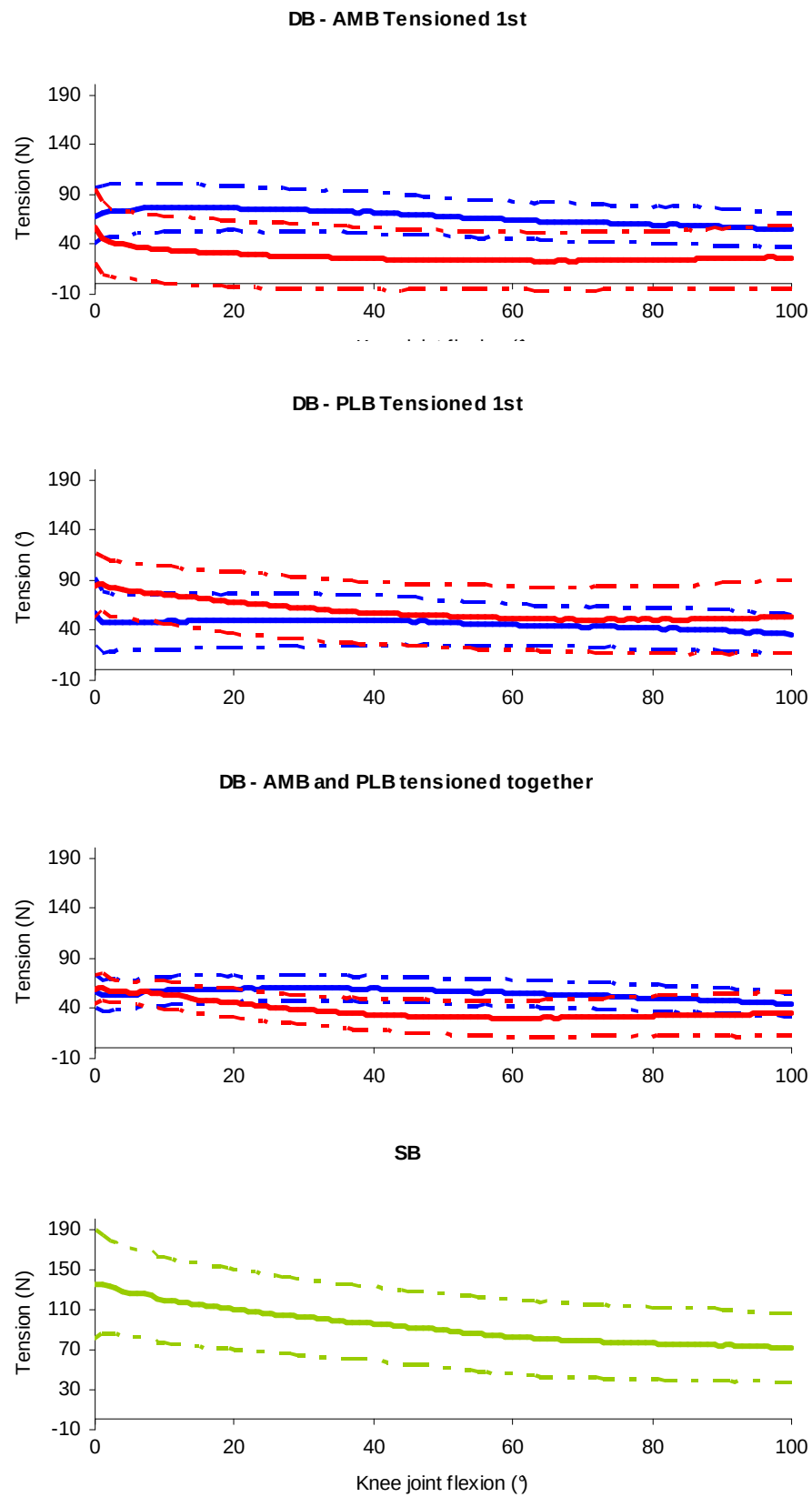


Figure 5.4: Tension in the AMB graft (blue line) PLB graft (red line) and SB graft (green line) under a 90N anterior force versus knee joint flexion, (mean $\pm$ SD, n=14).

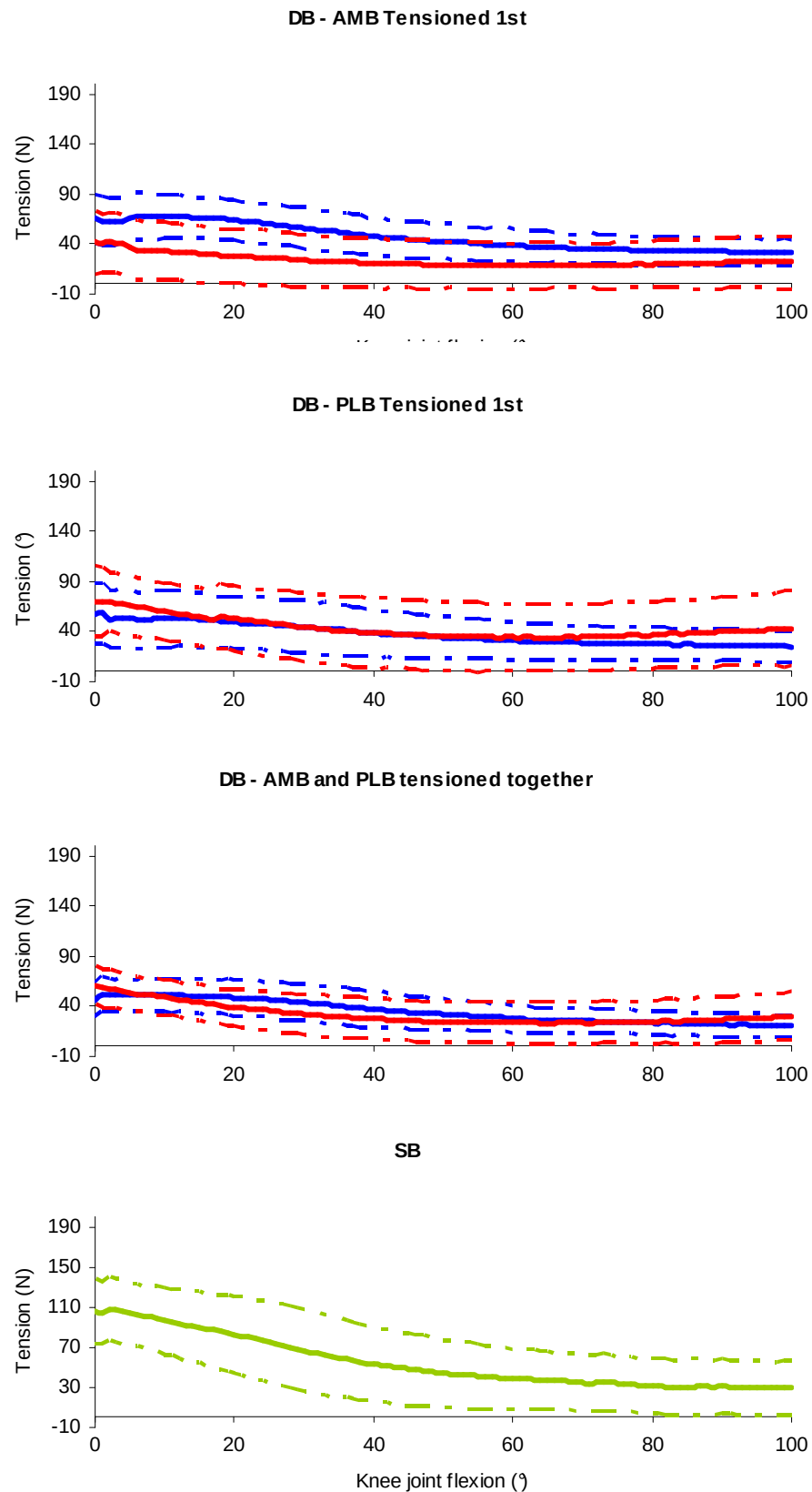


Figure 5.5: Tension in the AMB graft (blue line) PLB graft (red line) and SB graft (green line) under a 5Nm internal rotation torque versus knee joint flexion, (mean $\pm$ SD, n=14).

Although all the ACL reconstruction procedures were quite effective in controlling tibial anterior laxity, there were differences in their ability to restore intact knee laxity patterns (Fig. 5.6). Inconsistent matching of intact knee anterior laxity in flexion was recorded when the AMB was tensioned first and in SB reconstruction. The 95% CI in Figure 5.6 show that some knees had been over – or under – constrained, respectively. Significant overconstraint of the anterior translation limit was recorded in both flexion and extension when the PLB graft was tensioned first. The most consistent match to intact knee laxity across the range of motion was obtained when both bundles were fixed together.

Intact knee rotational laxity was controlled most consistently when both bundles were fixed together and when the PLB graft was fixed first although some small but significant differences from normal persisted in the flexed knee. Inconsistent control of knee rotations, indicated by the large confidence intervals, was recorded when the AMB graft was tensioned first, and by the SB reconstruction (Fig.5.7).

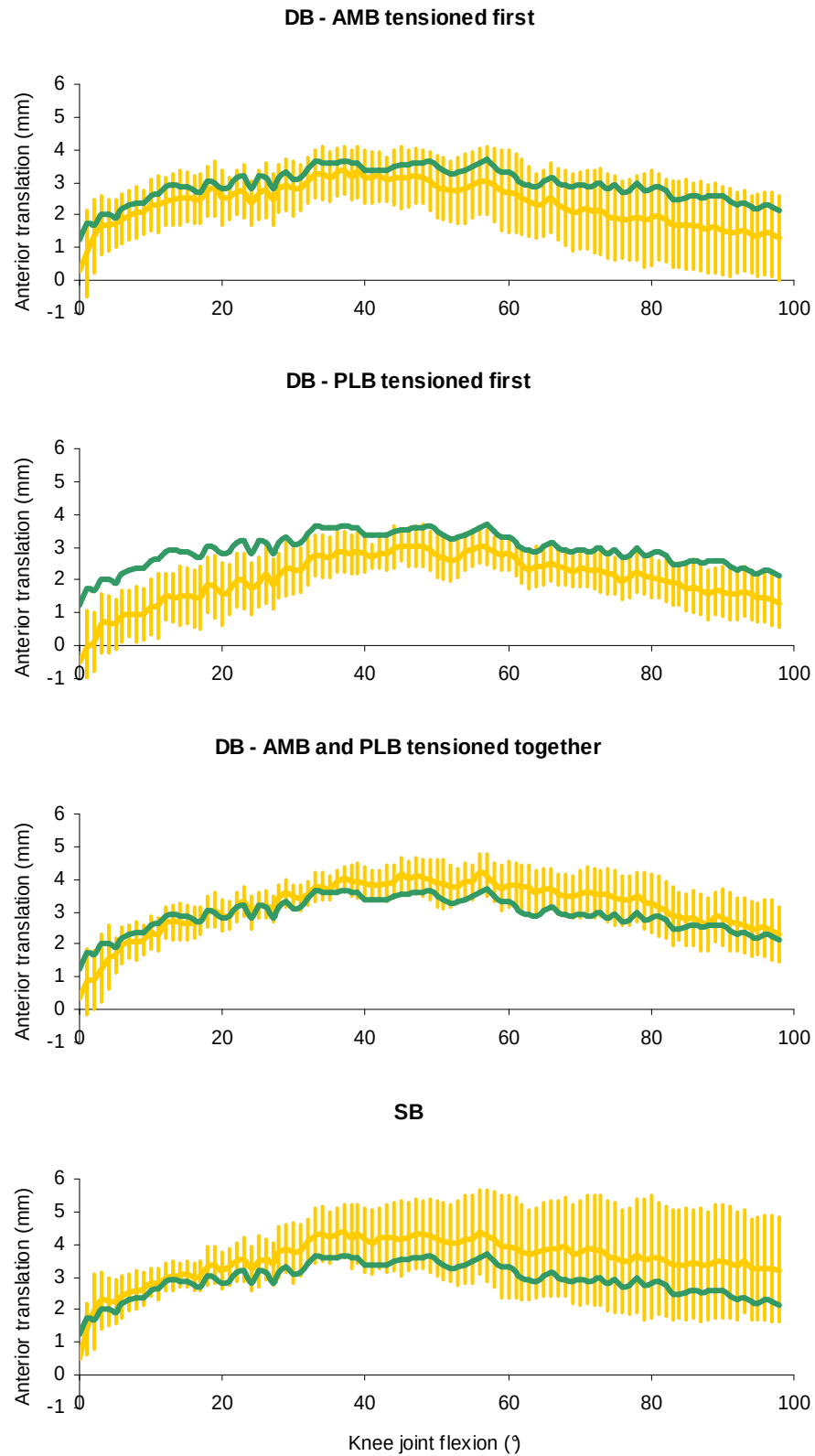


Figure 5.6: Mean (yellow line) $\pm$ 95% C.I. of the anterior translation limit change after the different ACL procedures. Green lines represent mean intact ACL anterior translation limit.

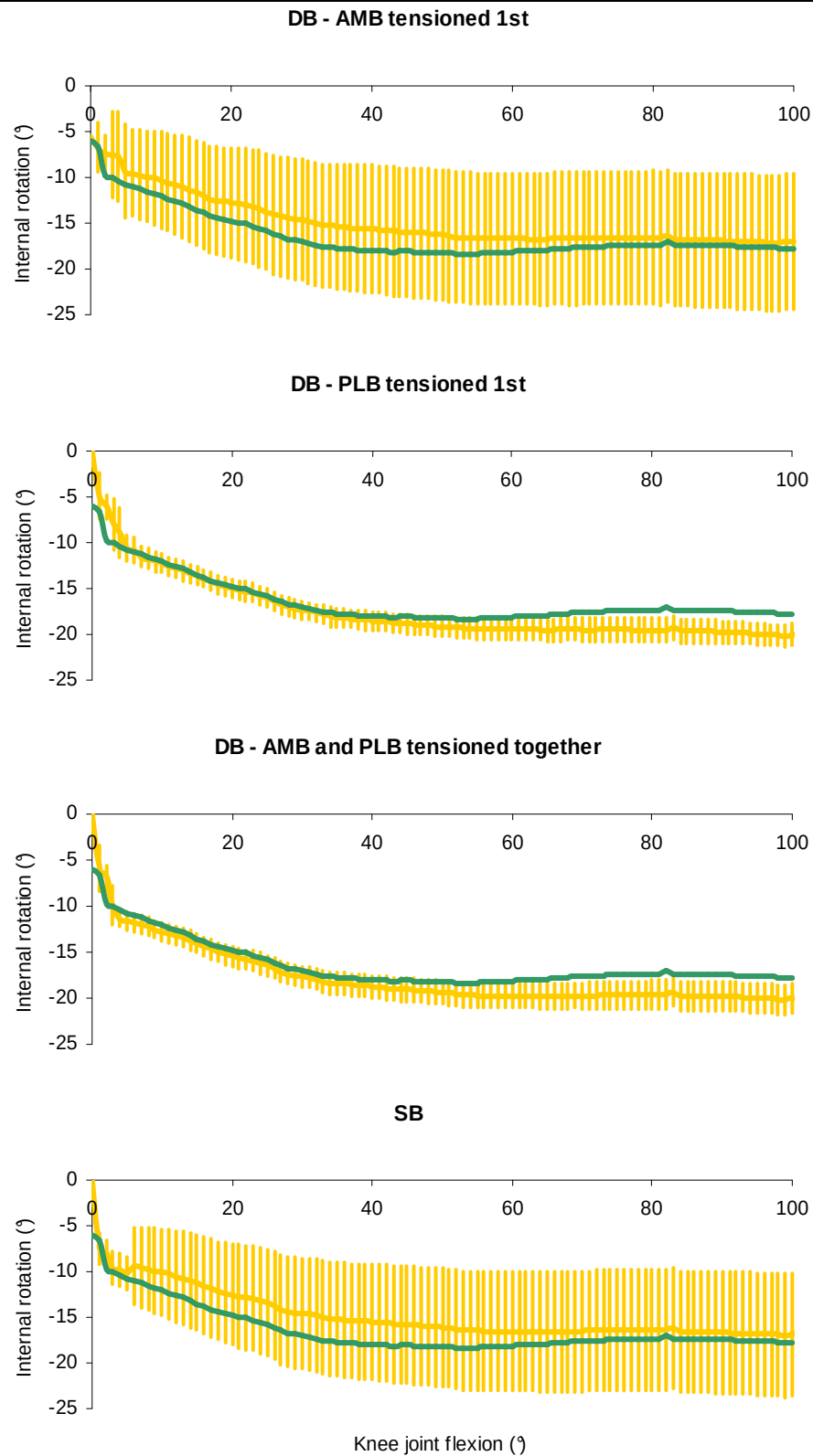


Figure 5.7: Mean (yellow line) $\pm$ 95% C.I. of the internal rotation limit change after the different ACL procedures. Green lines represent mean intact ACL internal rotation limit.

5.4 Discussion

The main finding of this investigation was that knee laxity and graft tension after DB ACL reconstruction were affected by the way the two grafts were tensioned. If the two bundles were fixed simultaneously at 20 degrees flexion and relatively low tension applied (17 N for each bundle), intact knee laxity restoration was obtained consistently with a low tension in the grafts throughout the range of motion. This was not possible with sequential bundle tensioning, which resulted in overconstraint of anterior laxity if the PLB graft was fixed first, or unpredictable anteroposterior and rotational laxity if the AMB graft was fixed first.

The tension patterns in the grafts, when the knees were flexing, were not affected by the tensioning strategy. In both bundles peak values were always recorded towards knee extension. In the PLB grafts, tension decreased rapidly when the knee flexed, while in the AMB grafts a small tension decrease was recorded. This reflects the behaviour of the native ACL bundles, which has been reported previously with different methodologies (Amis, Dawkins 1991; Bach, Hull, Patterson 1997; Fukubayashi, Torzilli, Sherman et al 1982, Gabriel, Wong, Woo et al 2004;). The rationale was therefore to tension the AMB, dominant in flexion, at 90° and the PLB, acting mainly in extension, at 20°, when a sequential tensioning protocol was used.

Sequential graft bundle tensioning required more tension than simultaneous tensioning to match the intact knee laxity with a double-bundle graft, especially when the PLB was tensioned first. This is a consequence of controlling the whole of the anterior laxity increase with one bundle only prior to tensioning the second bundle. When the AMB was tensioned first, a low tension (19 N) was needed because the AMB is the dominant bundle in flexion while the PLB is relaxed. Conversely, if the PLB was tensioned first at 20°, it required a high tension (43 N) because control of anterior laxity in extension is shared with the AMB.

Mechanical interactions between the graft bundles were shown clearly by sequential bundle tensioning. When the AMB was tensioned first to match the

intact knee laxity at 90° flexion, the subsequent tensioning of the PLB at 20° resulted in a tendency towards overconstraint in flexion likely due to the extra effect of the PLB (Fig. 5.6). Furthermore tensioning the AMB first in flexion resulted in anterior laxity match in extension as well, as documented by the minimal tension (5N in the majority of the knees) required in the PLB graft (Table 5.1). Similarly with the PLB tensioned first, overconstraint near extension can be explained by the additional stabilisation provided by the AMB fixed last in flexion and tightening in extension as well.

The SB reconstructions were tensed at 20° flexion to match the intact knee laxity, and that resulted in less consistent control of anterior translation and internal rotation than DB procedures in the flexed knee. The inferiority of SB compared to DB reconstructions has been documented previously for controlling tibial anterior translation (Radford, Amis 1991) and internal rotation (Yagi, Wong, Kanamori et al 2002). A more lateral SB femoral tunnel location has been advocated by some to improve the rotational control of the reconstruction (Yamamoto, Hsu, Woo et al 2004). In this study the SB tunnels were positioned at the centre of the native ACL attachment, which resulted in lower femoral positioning than conventional SB techniques which locate the femoral tunnel high in the intercondylar notch, close to the roof. Despite its more anatomical position, the SB graft was not sufficient to restore intact knee limits of rotation consistently.

Other authors explored in vitro the effects of the tensioning strategy on DB ACL reconstruction. Miura, Woo, Brinkley et al (2006), with a robotic device found that fixing the AMB graft first at 60° of flexion and then the PLB in extension resulted in AMB graft overload while simultaneous AMB and PLB graft at 30° of flexion resulted in PLB graft overload. Chen, Gadikota, Gill et al (2010) in a robotic study alternatively tensioned the PLB in extension and the AMB at 60° of flexion and found that the graft that was tensioned first had a lower in situ force than the native bundle and the graft that was fixed last had an higher in situ force than the native bundle. The main limitation of these two studies is that at the moment of final fixation the amount of tension was not adjusted to match intact knee laxity but arbitrary forces were chosen.

The role of the PLB of the natural ACL remains controversial; it has been suggested that it acts more as a rotatory than a translation restraint (Yasuda, Kondo, Ichiyama et al 2006). It is known that the natural PLB tightens when the knee extends and is then a restraint to anterior translation (Amis, Dawkins 1991), and that the PLB of a double-bundle reconstruction behaves in the same way (Yagi, Wong, Kanamori et al 2002). Observations in this study support this concept. A high graft tension is required to control anterior translation if the graft structure is only a secondary restraint. In this study the total tension required to fix simultaneously both bundles at 20° was less than that applied to the PLB only and to an 8 mm SB graft at the same angle, suggesting that the PLB was less efficient at controlling anterior translation. In addition, the PLB tension was still high with an internal rotation torque, while AMB tension decreased. Thus the different bundle function hypothesis, that the AMB controls anterior translation and the PLB rotation, respectively, is supported by these experiments.

These experiments found that transection of the ACL resulted in only a few degrees increase in rotational laxity that is likely to have only minimal clinical significance. This has been reported previously (Fukubayashi, Torzilli, Sherman et al 1982). On the other hand, the ACL controls the pivot shift phenomenon which is a combination of abnormal rotations and translations⁶ and is the best predictor of patients' subjective instability (Kocher, Steadman, Briggs et al 2004). Further understanding of the pivot shift phenomenon with regards to the limits of rotations and translations is needed in order to relate the effectiveness of laboratory procedures on the ACL to clinical instability. The present study has found that when both grafts of a double-bundle reconstruction were tensed simultaneously at 20 deg knee flexion the knees had much more consistent control of both anterior translation and internal rotation than single-bundle reconstructions.

Although this experiment suffered the drawbacks associated inevitably with work on elderly specimens in-vitro, that has been offset by the ability to make a series of comparative intra-specimen tests on a range of ACL reconstruction protocols. Further, the test set-up allowed carefully-controlled loads to be applied and full six degrees-of-freedom kinematic data to be collected by motion sensors attached

directly to the bones. There is much experience to show that laxity measurements in-vitro duplicate clinical laxity tests of the passive ligament restraints.

In conclusion, this study has confirmed in-vitro that DB ACL reconstruction is superior to an SB reconstruction in replicating intact knee laxity in both anterior translation and internal rotation. It has also demonstrated that graft tensioning procedure affects knee translations and rotations. Among the test protocols used, simultaneous tensioning of both bundles of a DB reconstruction at 20° knee flexion best restored intact knee laxity.

Based on the findings of this investigation it is thoughtful to export the laboratory experience of DB ACL reconstruction into the clinical practice. In the following chapters the surgical principles of ACL reconstruction will be discussed and DB ACL surgical strategies will be tested prior to introduce it in the clinics.

Chapter 6– SB ACL Reconstruction Technique

In chapters 3 to 5a method to experimentally investigate knee laxity through the use of combined loading to obtain an envelope of laxity or kinematics was described and applied to explore the function of the ACL and its bundles and to test the effectiveness of partial ACL reconstruction, SB and DB reconstruction. DB reconstruction was demonstrated to be superior in restoring intact knee laxity. Prior to the introduction of DB reconstruction into clinical studies, in this chapter the principles of conventional SB ACL reconstruction will be discussed.

6.1 Introduction

Modern ACL reconstruction techniques with an intra-articular graft passed into the knee joint in the direction of the native ACL fibers and secured to one tibial and one femoral bone tunnel have been developing for the last 30 years. In previous years ACL deficiency was approached in a non-anatomic way with extra-articular procedures which aimed at reducing anterior tibial translation (Lemaire, 1975).

In this chapter the principles of ACL reconstruction SB technique will be discussed with particular attention to graft choice and tunnel placement.

6.2 ACL grafts

The alternatives for an ACL substitute include autografts, allografts and synthetic ligaments used alone or as augmentation. At the present, autogenous tissues are most frequently used. Among available autografts, the hamstrings tendons (semitendinosus and gracilis) and the central third of the patellar tendon with its bone plugs (Bone-Patellar Tendon-Bone – BPTB) are the most common.

Until 1990 the BPTB was considered as the gold standard substitute in chronic ACL reconstruction. This popularity was due to the results of several experimental and clinical studies wherein BPTB appeared to be the natural substitute of ACL in terms of strength, stiffness, and stability. Evaluating the biomechanical properties of the ACL and several other human ligament substitutes in 18 human cadavers, Noyes, Butler, Grood et al (1984) found that the central one third 14mm wide BPTB was the single strongest autograft, with an average ultimate failure strength of 2900 ± 260 N, or 168% of the normal ACL. The stiffness was reported to be 685.2 ± 85.6 N/mm which is significantly greater than the normal ACL. The semitendinosus and gracilis tendons showed a lower ultimate failure strength, 1216 ± 50 N (70% of the normal ACL) and 838 ± 30 N (49% of the normal ACL), respectively, and a stiffness closer to that the normal ACL, 186.1 ± 9.2 N/mm and 170.9 ± 11 N/mm, respectively.

Woo, Hollis, Adams et al (1991) in a similar study on the tensile properties of the human femur-ACL-tibia complex, found significantly higher structural properties for the normal ACL. In this study the specimen was tested in an “anatomic” orientation so that the ACL fibers were tensioned uniformly. In young specimens, mean age 29 years, the mean ultimate failure strength was 2160 ± 157 N, with a mean stiffness of 242 ± 28 N/mm.

BPTB clinical results have had an overall success rate of over 80% even with a long-term follow-up (Aglietti, Buzzi, Giron et al 1997; Bach, Tradonsky, Bojchuck et al 1998). Based on these data most surgeons previously elected the BPTB as the graft of choice.

At the end of the 1980s some surgeons began to use the hamstring tendons. Marder, Raskind and Carroll (1991) performed a prospective study comparing the clinical outcomes of ACL reconstructions with BPTB and semitendinosus and gracilis (STG) tendons. They suggested that doubling the STG (DSTG) and applying an equal tension to the four bundles could double the tensile strength of the combined graft up to an ultimate failure load of 4108 N, or 250% of normal ACL strength. The clinical evaluation at an average follow-up of 29 months confirmed their assumption showing, no statistical differences between the two grafts in terms of postoperative Lachman test, pivot shift and instrumented laxity test with a KT-1000 arthrometer at 20 lbs.

Examining the biomechanical effects of doubling or combining multiple stranded tendon grafts, Hamner, Brown, Steiner et al in 1999 reported increasing values of ultimate load and stiffness with double G (average, 1550 N and 336 N/mm), double ST (average, 2330 N and 469 N/mm) and DSTG (average, 4090 N and 776 N/mm). They also compared the biomechanical properties of combined DSTG with and without equal tension in all tendon strands. Then, the results were compared to native ACL and a 10-mm BPTB graft. They concluded that the strength and stiffness of the DSTG graft are additive when the tendons are equally tensioned and that DSTG graft is stronger (4590 ± 674 N) and stiffer (861 ± 186 N/mm) than native ACL and BPTB graft. If equal tension is not used the tensile properties fall significantly (Fig. 6.1).

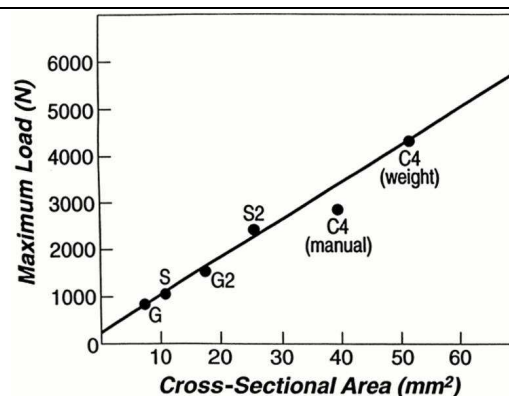


Figure 6.1: From Hamner et al (1999), changes in maximum load in relation to the cross-sectional area for gracilis (G), doubled gracilis (G2), semitendinosus (S), doubled semitendinosus (S2), four combined strands that were manually tensioned (C4 [manual]), and four strands tensioned with identical weights (C4 [weight])

On the other hand, Otero and Hutchenson (1993) comparing the postoperative success and stability of ACL reconstructions using the BPTB and the DSTG at 3-year follow-up, found that BPTB ensured better stability than DSTG. Furthermore, patients with acute conditions and those with intact menisci in the BPTB group had significantly greater stability ($p < .01$) compared to the same group of DSTG patients. The main difference between the two groups of patients was fixation: DSTG grafts were secured by sutures tied around a post on the femur and an acrylic spiked washer and cortical screw on the tibia, whereas the BPTB was fixed using interference screws at both sides.

In 1994 Aglietti, Buzzi, Zaccherotti et al, in a similar comparative study at 2.9-year follow-up, emphasized the importance of a strong fixation rather than type of graft employed. In the DSTG group they found a higher anterior tibial displacement in those cases in which the graft was not long enough to exit from the tibial tunnel and was then fixed with sutures around a post. When the tendons were long enough to exit the tibial tunnel and fixation was performed with spiked staples the side-to-side difference in anterior tibial displacement was comparable to the BPTB group. These different results in terms of stability among the DSTG cases imply that the tensile properties of the DSTG graft were probably more influenced by tensile properties of the fixation devices than with the BPTB graft.

In conclusion it is possible to state that DSTG and BPTB grafts are comparable in terms of mechanical properties. Furthermore rather than considering the strength and stiffness of the graft itself, the entire graft fixation composite complex should be considered.

6.3 *Tibial tunnel*

The tibial ACL insertion can be difficult to identify arthroscopically. The ligament fibres attach to an area delimited in its lateral and anterior border by the anterior horn of the lateral meniscus. Posteriorly, the ACL insertion is bounded by the posterior horn of the lateral meniscus; medially the attachment is limited by the

articular cartilage of the medial tibial plateau (Chapter 2). The shape and the cross-sectional area of the normal ACL vary from origin to insertion, in contrast with the uniform shape of our autogenous grafts. The BPTB is rectangular in cross-section, 10 mm wide and 4 mm thick. The DSTG graft has multiple bundles and is round in cross-section, with an average diameter of 8 mm. Grafts cannot replicate the broad insertion of the ACL. The surgeon must compromise when deciding where to place an 8 mm diameter tibial tunnel in the 19 mm insertional area of the ACL.

Anatomic placement of the graft requires the tibial tunnel to be placed within the boundaries of the normal ACL. Like the normal ligament, the anterior surface of the graft should be parallel to the slope of the intercondylar roof with the knee in maximum extension. To avoid anterior graft placement and subsequent impingement, the tibial tunnel should be drilled in the centre to the posterior half of the normal ACL tibial insertion. Placement of the tibial tunnel in the anterior half of the ACL insertion subjects the anterior fibres of the graft to roof impingement (Howell 1998).

Many authors tried to state the ideal tibial tunnel position in ACL reconstruction. In the early '80s the intra-articular entrance of the tibial tunnel tended to be positioned slightly anterior to the anatomic centre of the original ACL insertion, largely because of the original recommendation of Clancy, Nelson, Reider et al (1982) concerning the "anteromedial positioning", but the need for a notchplasty was great. Impingement against the notch can be avoided by using a tunnel placed in the center of the anatomic tibial insertion. A very posterior positioning on the tibia should be avoided because it is the least isometric, causing too much "elongation" toward extension (Bradley, Fitzpatrick, Daniel et al 1988; Penner, Daniel, Wood et al 1988; Sapega, Moyer, Scheneck et al 1990).

MRI studies reported by Howell and Taylor (1993) have shown that a sagittal anterior tibial placement error resulted in graft-roof impingement with subsequent graft failure and impingement in terminal knee extension. The pathognomonic findings of this phenomenon included a signal increase confined to the distal two-thirds of the intra-articular portion of the graft and posterior bowing caused by contact with the intercondylar roof (Fig. 6.2). Knees with moderately impinged

grafts at 2 years often became unstable if full extension was regained, or were stable if a flexion contracture persisted. Severe roof impingement was defined when the tibial tunnel was located totally anterior to the intercondylar roof. Knees with severely impinged grafts regained full extension but became unstable within 6 months of implantation.

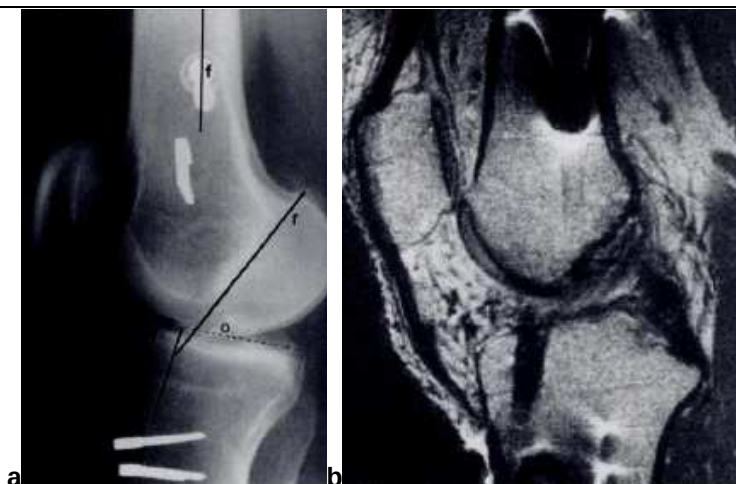


Figure 6.2: from Howell et al (1993), (a) x-ray showing a severely impinged graft which on mri (b) shows high signal intensity

To find a correct tunnel position, Good and Gillquist (1993) advocated placing the center of the intraarticular exit of the tibial tunnel at 33% of the anteroposterior diameter of the tibial plateau. Khalfayan, Sharkey, Alexander et al (1996) reported that placing the centre of the tibial tunnel at 20 % to 40% of the A-P diameter of the tibia significantly improved knee stability and motion compared with tunnels located outside this range. They used this criterion, as well as a femoral tunnel centre position of greater than 60% along the Blumensaat's line (i.e. projection of the roof of the intercondylar notch on the lateral femoral view x-ray) to define Group I patients. Group II patients included all others who did not meet Group I criteria. In Group I, 79% of patients had stable knees as defined by KT-1000 arthrometer testing and 69% of patients had good or excellent Lysholm scores. Only 22% of patients in Group II had stable knees on instrumented testing, and only 50% had good or excellent results based on the Lysholm scores. The error was in positioning the tibial or femoral tunnels anterior to the desired position. An anterior tibial tunnel placement led to graft impingement in extension with persistent flexion contracture or graft attrition and failure. At the

femoral side an anterior graft tightened with flexion, again leading to loss of motion or attrition.

Supporting this concept, Marzo, Bowe, Warren et al (1992) reported that an anterior BPTB graft placement causes a fibrous nodule (cyclops) formation from partial graft rupture caused by graft impingement, leading to clinical mechanical symptoms like pain and extension loss, after ACL reconstruction. The authors recommended sagittal placement of the tibial tunnel for ACL reconstruction in the central one third of the original ACL tibial insertion.

Morgan, Kalman, Grawl et al (1995) introduced a new tibial guide (Arthrex Inc, Naples, FL) using the PCL as a reference. The centre of the tunnel was 7 mm from the PCL with the knee at 90 degrees. This guide was designed to obtain (a) the smallest sagittal divergence angle between the tibial tunnel and the intra-articular portion of the ACL graft, parallel to the intercondylar roof in full extension, (b) sufficient tibial tunnel length to keep the graft from exiting distally from the tunnel (tunnel mismatch), and (c) an intraarticular tibial tunnel entrance positioned sagittally central in the original ACL insertion such that the completed reconstruction remains impingement-free in full knee extension without the need for notchplasty. However, it can be argued that any aimer used to abut against the PCL may produce ambiguous results because PCL tissue may yield during measurement; it is also unlikely that the center of all tibial tunnels should be exactly 7 mm anterior to the PCL, regardless of patient size. Furthermore, neither the difference in posterior wall position for different tibial tunnel diameters, nor the physiologic roof angle and knee recurvatum variability in different patients were considered.

Given that the normal ACL lies parallel and posterior and grazes the intercondylar roof with the knee in maximum extension, it was thought that the intercondylar roof could be used as a rigid landmark to position the guide instead of relying on mutable, soft-tissue structures. Therefore, Howell (1998) designed and tested a guide (One-Step, Impingement-Free Tibial guide, Arthrotek, Inc., Ontario, CA) (Fig. 6.3) that customized the tibial tunnel by keying-off the intercondylar roof and drilling the guide wire with the knee in full extension.

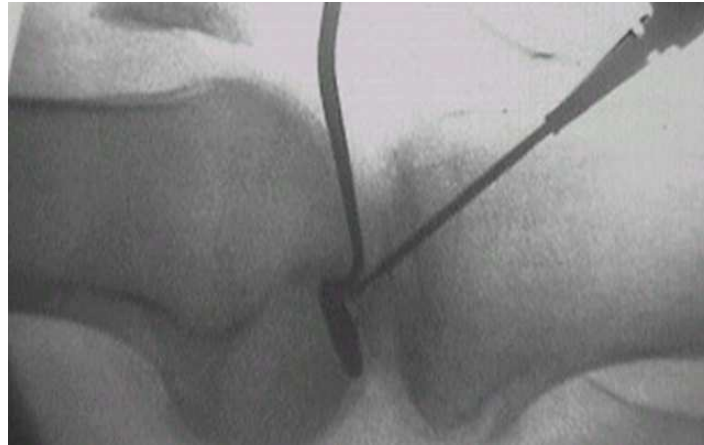


Figure 6.3: intraoperative x-ray of the Howell guide which allows to drill the tibial tunnel in extension and avoid roof impingement.

The prevention of roof impingement with this technique was validated with MRI and lateral radiographs of the extended knee (Howell 1998). Some roof or notchplasty is still required after use of the guide because the stress relaxation and the remodelling process of the neoligament usually result in a minimal residual anterior tibial translation that could induce some graft impingement.

The guide should be oriented in the coronal plane so that the guide wire forms an angle of 70 to 75° with the medial tibial joint line. In this way the medio-lateral location of the intraarticular tibial tunnel exit will be at about 45% of the width of the tibial plateau, from the medial border, or between the spines.

Howell, Wallace and Hull (1999) in 14 ACL reconstructions revealed a relationship between the angle and position of the tibial tunnel in the coronal plane and the tension in the graft from 50 to 80° of flexion. As the angle of the tibial tunnel increased the graft tension increased at 50°, 60° and 80° of flexion. As the tibial tunnel position shifted medially, the tension in the graft increased with knee flexion. The tibial tunnel angle was a stronger predictor of tension increase of the graft with knee flexion than the tibial tunnel position. No significant relationship was found between the angle and the position of the tibial tunnel in the sagittal plane and the tension in the graft during flexion. The authors concluded that a graft in a medial and vertical tibial tunnel has an unphysiological raise in tension during flexion while the normal ACL shows a low unchanging tension raise profile. The raise of tension in flexion however did not affect the

stability and the clinical outcome at the one-year follow-up, however. On the other hand, a subsequent investigation with a longer followup showed that reconstruction with vertical grafts are susceptible to increased laxity or flexion loss which has been explained as ACL graft impingement on PCL in flexion (Howell, Gittins, Gottlieb et al 2001). This concept was supported by a biomechanical laboratory study as well (Simmons, Howell, Hull 2003) which demonstrate that vertical graft tension raise in flexion could be lowered by excising the lateral aspect of the PCL.

6.4 *Femoral Tunnel*

A correct femoral tunnel position during intra-articular ACL reconstruction is critical to a successful result.

To avoid the confusion related to different schemes employed in the literature for describing positions and directions within the knee, the “surgical nomenclature” described in Chapter 2 will be used. The surgeon, in fact, needs to describe things as they are seen through the intercondylar notch, when the knee is flexed . In this case positions are related to the roof of the notch: “superficial-deep” and “superior-inferior”. Standard anatomic nomenclature will be reported as well.

The femoral attachment site has a greater effect on graft length changes, as the knee flexes and extends, than the tibial attachment. Displacements along the line of the roof of the notch are particularly significant. In a minimum 5-year follow-up of 89 arthroscopic assisted ACL reconstructions it was found that 88% of the knees with a correct deep and superior (proximal) placement of the femoral tunnel showed satisfactory stability. This meant that the anterior margin of the tunnel was located beyond the anterior 60% of condylar width. A superficial (anterior and distal) placement of the femoral tunnel was associated with graft failure in 62.5% of the cases (Aglietti, Buzzi, Giron et al 1997).

Current surgical techniques are insufficient to duplicate the complex geometry or fiber-tensioning patterns of the ACL. The surgeon's purpose is basically limited to duplicating the global function of the deficient ligament. The ACL is not totally isometric and only few fibers are nearly isometric over the full range of motion under certain, specific, loading conditions. A nearly isometric behaviour of the ACL substitute is desirable, with a maximum of 2 to 3 mm lengthening of the graft toward extension (Amis, Dawkins 1991; Amis, Beynnon, Blankevoort et al 1994). If the cruciate ligament substitute is not positioned isometrically, the distance between its femoral and tibial insertion points will vary during knee motion causing graft over-constraint at various degrees of knee flexion, and graft slackness, resulting in increased joint laxity at other degrees.

Isometry is widely influenced by femoral tunnel positioning. Positioning the femoral tunnel close to the insertion of the AMB fibers (deep and superior in the notch with the knee in flexion) is desirable to achieve a nearly isometric behaviour of the graft.

Using a steel cord to replace the ACL in cadaver knees, Hoogland and Hillen (1984) found that only a deep-superior (proximal) femoral hole gave the best and most consistent results. Evaluating the length changes between ACL insertion sites in 33 normal cadaver knees, Odensten and Gillquist (1985) reported that the distance between the central points of the insertion areas on the tibia and the femur did not change throughout the whole range of motion. Changing the femoral site to the over-the-top or a more superficial (anterior-distal) position caused an increase in length during both extension and flexion of the knee,...

Graf and Vanderby (1993) observed that while most of the anatomic ACL fibres are nonisometric, an isometric placement of ACL substitutes is desirable to allow knee motion without high ligament strains. In an experimental study, the authors found that the most isometric record was obtained by a femoral hole close to the roof of the intercondylar notch and 5 to 10 mm anterior to the over-the-top position. They also suggested that large increases in length towards flexion are indicative of a too-superficial (anterior and distal) femoral placement, whereas increases toward extension may be due to a too deep placement either in the tibia or in the femur (proximal and posterior).

Bradley, Fitzpatrick, Daniel et al (1988), using the four-bar linkage model of the knee to predict length changes in the ACL showed that femoral displacements in the superficial and deep (from anterior and distal to posterior and proximal) directions along the line of the roof are more important than displacements in the superior (proximal) and inferior (distal) directions perpendicular to the line of the roof.

Hefzy, Grood and Noyes (1989), using an instrumented spatial linkage to generate contour maps, similarly measured length changes between tibial and femoral attachments, and on the femoral condyle they designed an oval contour map, with a roughly proximal to distal long axis, which contained isometric points within 2 mm of length change. Points superficial (anterior and distal) to the isometric area showed increased length patterns with flexion, while points deep (posterior and proximal) to it showed increasing length with extension.

Sapega, Moyer, Scheneck et al (1990), implanting excursion wires in the anteromedial, central and posterior fibres of the normal ACL ligament, recorded isometry data through a 0 to 119° knee flexion arc of motion, with the femur stabilized and leg freely dependent before and after transection of the ACL, with and without the application of an axial force to the tibia to avoid the tibiofemoral separation that occurs in flexion. They found that in the normal ACL the anteromedial fibres were the most isometric (average, 2.9 mm of maximum length change). Although the magnitude of the displacement between insertion sites of the three bundles varied, the overall profile of the curves was similar, with some slackening in the first 30 to 45° flexion, followed by further tensioning of the ligament. The authors concluded that with the conditions used in surgery (femur horizontal, leg dependent, and quadriceps relaxed) there is no absolute isometry, and that the anteromedial fibers showed the lowest deviation. Their deviation was further reduced by preventing distraction of the joint by gravity. Under these conditions, up to 3 mm of length change could be accepted, providing that the normal pattern of relaxation is achieved in the first 45° of flexion followed by some retightening.

Zavras, Race Bull et al (2000), in a cadaver study independently compared the “isometric points” described by other authors in previous works (Blankevoort,

Huiskes, van Kampen 1991; Cazenave, Laboureau 1990; Fleming, Beynnon, Johnson et al 1993; Friederich, O'Brien 1992; Hefzy, Grood, Noyes 1989; Muneta, Yamamoto, Sakai et al 1993; Odensten, Gillquist 1993; Schutzer, Christen, Jakob 1991; Schutzer, Christen, Jakob et al 1988). "Isometric points" were defined either geometrically, following the coordinate directions of previous works, or anatomically (Fig. 6.4).

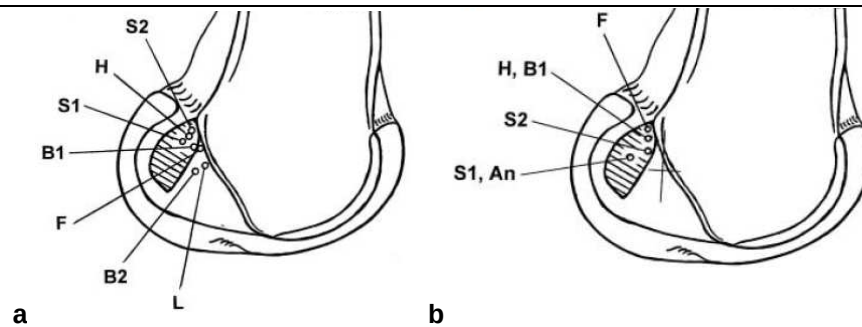


Figure 6.4: Zavras et al points from previous works which were located geometrically (a) or anatomically (b).

As a result not all the tested points were isometric (Fig. 6.5). Zavras, Race, Bull et al (2000) were able to describe an area close to the posterior end of the Blumensaat line where all the real isometric points were located.

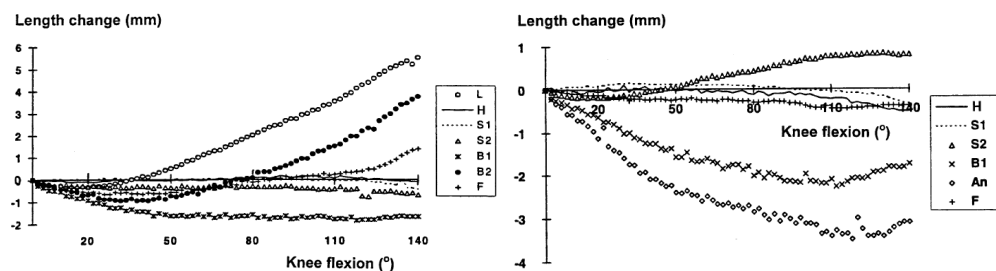


Fig. 6.5: from Zavras et al (2000), graft length changes according to the different "isometric points" illustrated in Fig. 6.4

Amis and Dawkins (1991) directly measured the lengths of the actual ligament bundles using wires within an intact ACL. All bundles elongated during the final 30° of knee joint extension; none was really isometric. The AMB was closest to isometricity. In general, the AMB tightened in flexion and the PLB slackened.

The effectiveness of the intraoperative isometry measurement to confirm correct tunnel positions and excursion length and tension patterns of the graft in ACL

reconstruction was also evaluated by Good and Gillquist (1993). In vivo measurements were taken in 10 patients undergoing reconstruction due to chronic ACL deficiency. The drill channels were placed transcondylarly, using an isometric drill guide (Stryker Inc., Kalamazoo, MI). The drill guide was introduced at 90° of knee flexion through an anteromedial mini-arthrotomy. Drilling was conducted along a straight line through the tibia and the femur using a 2mm drill bit. The absence of impingement and the location of the drill channels on the tibia and femur were documented with a thin wire in situ and Polaroid prints of the freeze frame captured image amplifier screen in lateral projections of the knee. The correct location of the femoral drill channel was defined as the interval between 62% and 70% of the total condylar depth in a deep and superior (from anterior and distal to proximal) direction, measured on a line parallel to the Blumensaat's line.

In a previous study by the same authors (Good, Odensten and Gillquist 1987), this interval was found to correspond with the anatomic attachment of the ACL. Change in intraarticular length of a 1.2 mm test ligament (braided multifilamentous Kevlar cord), measured with an isometer, was correlated to the tension created in the same test ligament after fixation and measured with a piezoelectric load cell. The knee was passively flexed through the range of 0 to 100° with the patient under general anaesthesia. Statistical and visual correlation was good in individual knees. A correlation between total length change and maximum tension of the test ligament for all knees grouped was also found. Individual knees showed a large variation in ability of the tissue to absorb load, resulting in a wide range of N/mm ratios between length and tension. In 9 of 10 knees the length change pattern could be used to identify the location of the femoral drill channel, as determined on the intraoperative lateral projection of the knee. The authors concluded that the intraoperative isometry measurement could be used to predict the tension pattern in the reconstructed knee, but not the magnitude of the tension.

The same authors (Good, Odensten and Gillquist 1994) published a clinical study on knee stability after ACL reconstruction using BPTB graft in 24 patients at the 2-year follow-up. The results were evaluated in correlation to data obtained in surgery on the femoral ligament insertion location and the change in intra-articular

fixation distance, measured with an Isometer. Patients for whom the graft fixation angle coincided with the angle of minimum intra-articular fixation distance, and patients who had a superficial femoral ligament insertion location (anterior and distal), more than 2 mm to the center of the normal ACL insertion area, showed larger anterior tibial displacement than other patients. In these patients the failure rates were higher than for the other patients. No correlation was found between displacements along the line of the roof of the notch and the magnitude of the change in intra-articular fixation distance. The authors concluded that the superficial (anterior and distal) femoral locations lead to a larger anterior tibial displacement after 2 years than do central or deep (proximal) locations and that the magnitude of the fixation distance is less important than the pattern. Intraoperative isometry measurements are of value, in that they supply patterns of change in fixation distance, but femoral tunnel location in the center or deep (proximal) to the anatomic ACL attachment area achieves better results in terms of sagittal stability at follow-up.

As opposed to the low reproducibility found in the intraoperative isometry measurements, a high correlation has been demonstrated between the location of the femoral tunnel, measured on lateral radiographic projection, and the objective knee stability evaluated at follow-up. As previously reported, Good and Gillquist (1987) found the mean center of the anatomic attachment of the natural ACL to be located at 66% on average of the total femoral condylar depth in a posterior direction, as measured just below and parallel to the Blumensaat's line.

In a 7-year follow-up study of 44 open ACL reconstructions using the central third patellar tendon and a lateral extra-articular tenodesis, Aglietti, Buzzi, D'Andria et al (1992) used a similar radiographic method to determine location of the anterior margin of the exit hole. They found that at 50% to 65% of the anterior-posterior width of the condyle, knees with a more superficial femoral hole showed a greater anterior tibial displacement (average, 4.7 mm) than knees with a deeper femoral hole, located at 60% to 70% (average, 2 mm). The importance of the femoral tunnel placement was confirmed by the same authors (Aglietti, Buzzi, Giron 1997) in a more recent 7-year follow-up study of 89 arthroscopic assisted ACL reconstructions using the central third patellar tendon. Eighty-eight percent of the knees with a correct deep placement of the femoral tunnel (beyond 60% of the

sagittal length of the condyles) showed satisfactory stability. A superficial placement of the femoral tunnel in the anterior 50% of the width of the condyles, was associated with graft failure in 62.5% of the knees examined.

After the introduction of the arthroscopic assisted ACL reconstructions, three major surgical techniques have been developed to produce the femoral tunnel: the double incision technique (Hewson 1983), the single incision transtibial technique (Hardin, Bach, Bush-Joseph et al 1992), and the single incision technique through the anteromedial portal (Scranton, Pinczewski, Auld et al 1996).

The double incision technique requires an anteromedial incision for the tibial work and a lateral approach for the lateral femoral metaphysis. Front-entry or rear-entry “C” guides are employed to introduce a Kirschner (K) wire outside-in into the lateral femoral metaphysis (Fig. 6.6).

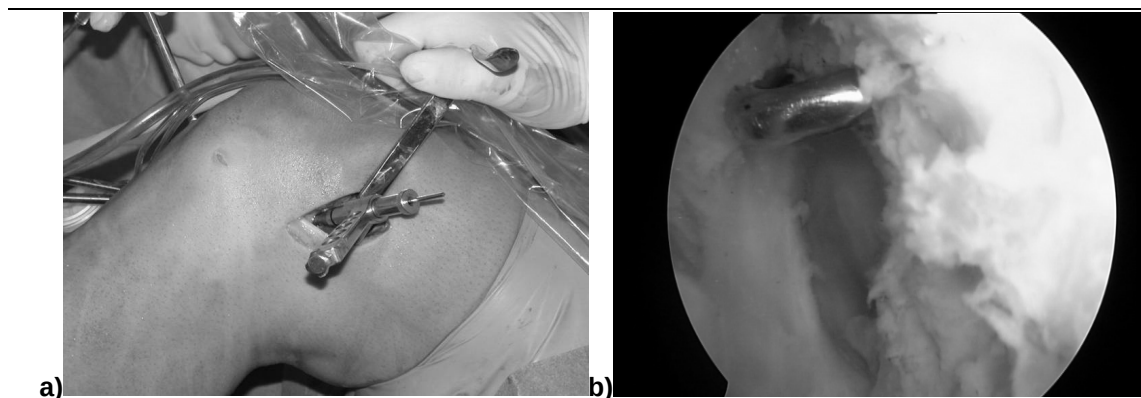


Figure 6.6: Double incision technique. Rear entry guide inserted into the knee joint through a lateral incision (a). Arthroscopic view of the tip of the guide (b).

In the transtibial technique, the femoral tunnel is drilled inside-out through the tibial tunnel by using special endoscopic femoral guides and atraumatic reamers, with the knee at 70 to 80° of flexion (Fig 6.7).

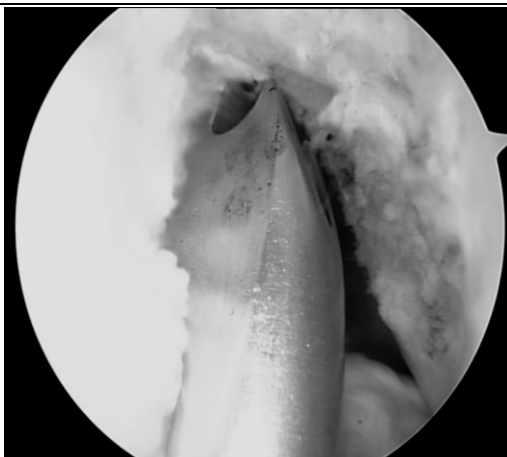


Figure 6.7: single incision transtibial femoral aimer hooking in the over the top position

Using the anteromedial technique the femoral tunnel is produced from inside through a low anteromedial portal, using atraumatic reamers with the knee in maximum flexion (Fig. 6.8). With this approach drilling is completely free-hand, then a proper anatomic knowledge of the femoral ACL attachment is required. Furthermore in deep flexion the visualization of the lateral of the notch wall through the anterolateral portal is poor (Fig 6.8 b). In addition the drill bit may damage the lateral femoral condyle (Zantop, Haase, Fu 2008).



**Figure 6.8: Transportal tunnel drilled through an accessory (arrow) medial portal (a).
Arthroscopic view of the k-wire (b).**

In the cadaver model (15 specimens), Giron, Buzzi and Aglietti (1999) performed an experimental study to determine whether a correct deep position of the femoral tunnel could be equally obtained with the three different techniques. Each

technique was employed in 5 cadavers for a total of 10 knees. The knee was approached through an anteromedial arthrotomy. The ACL was visualised by removing the overlying synovium. The femoral insertion area of the AMB was visually identified. A lateral radiograph with superimposition of the femoral condyles was obtained before and after drilling the tunnel. For each technique the position of the tip of the guide wire was kept flush with the wall of the notch, and the location of the anterior margin of the femoral tunnel was measured using the quadrant method described by Bernard, Hertel, Hornung et al (1997). The tip of the guide wire was located on average at 66.5% to 75% of the width of the condyles along the Blumensaat's line and at 11% to 15% of the height of the condyles (perpendicular to the Blumensaat's line). The differences between the three techniques were not statistically significant. Overdrilling the K-wire with a 10-mm drill bit causes some superficial and inferior displacement of the femoral insertion along the notch. The superficial margin of the intra-articular exit hole was located on average at 64% to 66% of the condyle width along the Blumensaat's line. None of the femoral holes was more superficial than 60%. The inferior margin of the intra-articular exit hole was located on average at 26.5% to 28% of the height of the condyles. Again, the differences between the three techniques were not significant.

Differences in the orientation of the femoral tunnel were observed. The inclination of the femoral and tibial tunnels was measured in relationship to the joint line. The angulation of the tibial tunnel was similar for the three techniques ranging from 67 to 72 degrees on average. Significant differences were found between the angulation of the femoral tunnel for the double incision technique (37 degrees), the transtibial (68 degrees) and the anteromedial (50 degrees). As expected, the divergence between femoral and tibial tunnels was minimal when using the transtibial technique. A wide divergence among the tunnels resulted from the double incision technique, 35 degrees on average, due to the more horizontal angulation of the femoral tunnel in the coronal plane. The divergence was intermediate in the anteromedial technique (average, 17 degrees). An increased divergency, anyway, implies that the tunnel is mainly on the wall (i.e. more anatomic) than on the roof of the notch as it is when drilled through the tibia.

Other investigators on the other hand criticised the transtibial approach labelling it as non-anatomic. Arnold, Kooloos and Van Kampen (2001) scoped 5 cadaver knees and showed that they could not reach the native ACL attachment with a transtibial approach but only the more proximal fibres, with most of the femoral tunnel involving the roof of the notch.

More recently in a computed tomography study after transtibial ACL reconstruction on 32 knees, Kopf, Forsythe, Wong et al (2010) documented that tunnels had a tendency to be anterior (i.e. high) to real ACL attachment (Fig. 6.8).

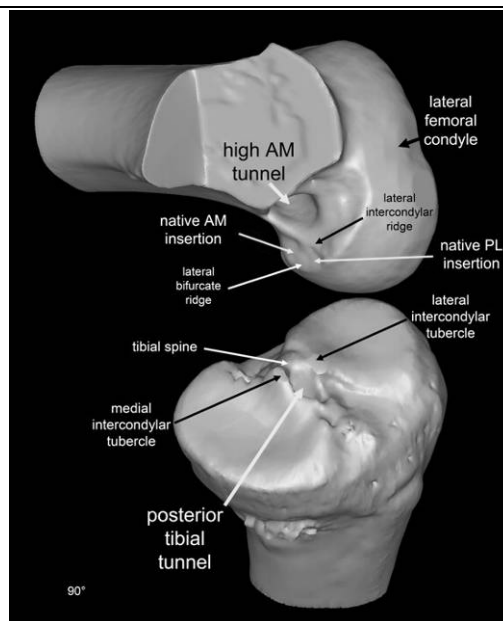


Figure 6.8: from Kopf et al (2010), CT documentation of an anterior (i.e. high) femoral tunnel drilled through a transtibial approach

6.5 Conclusions

Intra-articular SB reconstruction is nowadays the treatment of choice of ACL rupture. Autologous grafts are the most employed and recent advances in fixation devices increased the popularity of hamstring tendons autografts. Tibial and femoral tunnel positioning is crucial. On the tibia roof and PCL impingement must be avoided, so sagittal and coronal tunnel placement are critical. On the femur

the tunnel must lie deep in the notch to avoid abnormal graft tightening and reconstruction failure. Tunnel positioning is affected by the employed surgical approach. The transtibial approach, which is perhaps the most common, seems to be less anatomic than other techniques, though ensuring a safe deep positioning. Other approaches are probably more anatomic but rely mainly on the surgeon's experience and knowledge of anatomy.

Chapter 7 – Validation of the Tibial Howell Guide

In Chapter 6 the surgical principles and outcomes of conventional single bundle ACL reconstruction were reviewed and discussed with particular regard to tibial and femoral tunnel placement. On the tibia the importance of roof impingement avoidance was emphasized. In this chapter a study will be presented in which a commercially available roof referencing tibial guide is tested and validated.

7.1 Introduction

ACL reconstruction is a common orthopaedic procedure and satisfactory results are achieved in the majority of cases. Despite the range of grafts and fixation devices employed, correct tunnel placement remains the main determinant of the final outcome and a malpositioned tunnel is likely to result in instability or in lack of recovery of the range of motion (Chapter 6). An anatomic position of the graft is desirable but identifying the correct tunnel exit point within the whole attachment area of the ACL may be a challenge. Furthermore, usually at arthroscopy and especially in chronic lesions, no ACL remnants may be identified. Many authors have studied the correct intra-articular position of the tunnels and several methods to achieve it have been developed (Giron, Buzzi, Aglietti 1999; Howell 1998; Khalfayan, Sharkey, Alexander et al 1996; Jackson, Gasser 1994; Morgan, Kalmam, Grawl 1995). Most of the existing methods either need intraoperative X-rays to confirm the location or rely on “point and shoot” guides aiming at intraarticular landmarks. The result is that tunnel positioning is mostly surgeon dependent and so reproducibility may be lacking.

The aim of this investigation was to verify in cadaver knees the ability of the Howell tibial drill guide system (Arthrotek) to place the tibial tunnel in the correct position. This system locates the tibial guidewire path by referencing from the roof of the femoral intercondylar notch of the fully extended knee. The guide includes an offset between the probe that locates against the roof of the notch, and the path of the guidewire, that is larger than the radius of the graft tunnel, thus it should prevent graft impingement. As the wire is drilled in maximum extension the system should prevent roof impingement even in knees that hyperextend. Because the natural ACL fits against the roof of the notch in the extended knee, it was hypothesised that this type of drill guide would result in the tibial tunnel guidewire exiting the tibia within the anatomical ACL attachment. However, Buzzi, Zaccherotti, Giron et al (1999) found that the intersection of the extended line of the roof of the femoral intercondylar notch was extremely variable, from 22 to 41% of the anterior-posterior width of the tibial plateau, suggesting that the tunnel may not always be within the anatomic ACL attachment.

Although the originators of the guide used here have published data to support an anatomical placement (Simmons, Howell, Hull 2003), the design of the guide has been modified recently and it has been implemented with a larger intrarticular probe to ensure a more lateral tunnel placement. Furthermore the coronal angulation has been reduced from seventy to sixty-five degrees to allow the femoral tunnel to be drilled in a more lateral (i.e. anatomical) position in the notch.

7.2 *Materials and Methods*

Twenty-one fresh-frozen knee specimens were used. They had been obtained with informed consent from relatives in accordance with a local research ethics committee permission. In all the knees the extensor mechanism had previously been completely removed. None of the knees showed advanced signs of osteoarthritis. The ACL and PCL were intact and competent in all the specimens, and none of the knees had abnormal laxity in extension. The femoral and tibial

shafts were potted in bone cement and at least 10 cm of bone were left available from the joint line in each knee.

The ACL AMB and PLB were identified as described in Chapter 2. The ACL was then cut in its midsubstance and the tibial attachments of the two bundles were marked with red ink after the remnants of the bundles had been cut from the bone. The "over the back" position and the lateral aspect of the medial spine were marked with red ink as well (Chapter 2). The femoral shaft was then clamped in a table vice which allowed knee flexion and extension in a vertical plane. A 40 cm intramedullary rod was inserted into the tibia in order to extend the knee, resembling the intraoperative situation in which the knee is held in maximum extension from the heel. A two kilograms mass was hung on the proximal part of the rod to resemble the weight of the leg in normal conditions, resulting in a posterior drawer stress to the knee when the tibia was horizontal. To drill the tibial tunnel the Howell 65° tibial guide (Arthrotek Inc.) was employed according to the manufacturer's instructions (Fig. 7.1).

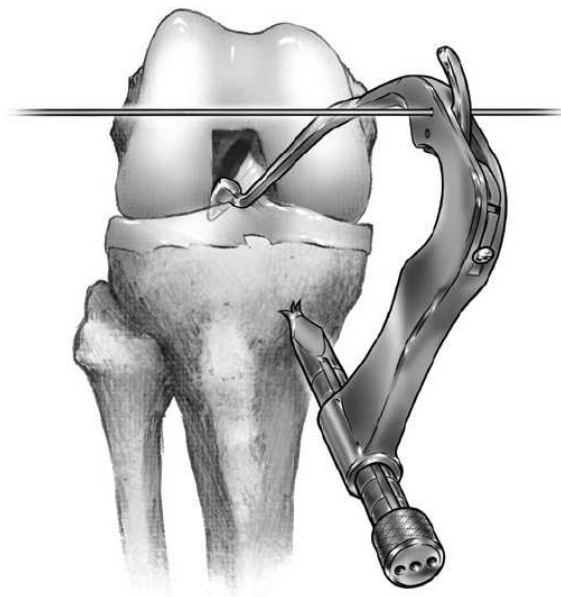


Figure 7.1: 65°Howell guide inserted through the anteromedial portal

The guide controls the path of the tibial guidewire in the extended knee, that is offset away from the roof of the intercondylar notch. It includes a probe which is inserted into the flexed joint through the anteromedial arthroscopic portal and is placed into the notch (Fig. 7.2).

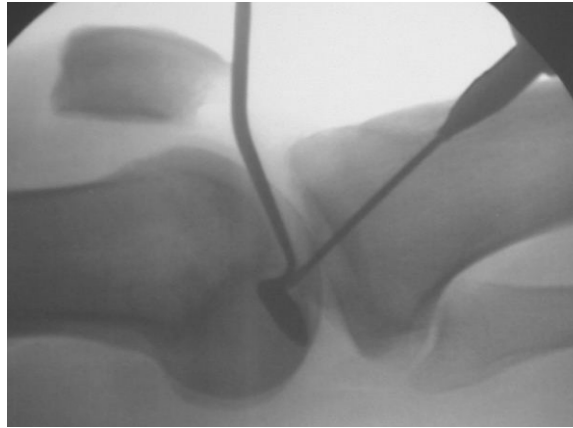


Figure 7.2: intraoperative x-ray showing the guide probe against the intercondylar roof

When the knee is in full extension the probe is trapped between the femur and the tibia and its correct position must be checked arthroscopically (Fig. 7.3). The probe is then pulled anteriorly until its anterior aspect is in contact with the roof of the notch.

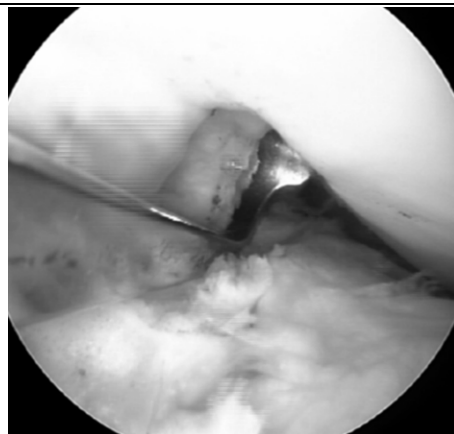


Figure 7.3: the probe of the 65° Howell guide in the intercondylar notch

The probe is part of a C-arm which allows the guide wire to be drilled through a telescopic guide barrel on the anteromedial aspect of the proximal tibia. The guide has a reference pin which crosses the C-arm at 65° and this helps to align the tunnel with a 65° coronal angle (Fig. 7.4). The guide barrel has three parallel bores, allowing the tunnel to be moved to a central position or a more lateral one if the first K-wire seems to be too medial (Fig. 7.1). When the guide wire is drilled into the joint, it comes into contact with the probe, leaving 6 mm between the roof and the wire in order to prevent roof impingement.

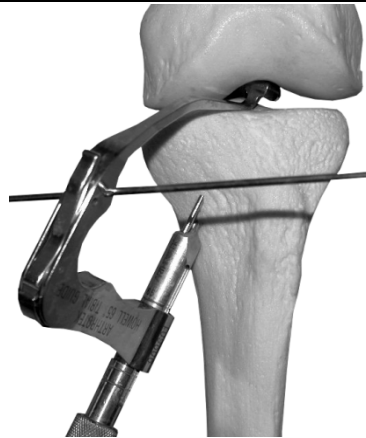


Figure 7.4: Howell guide with the 65° reference pin for coronal alignment

With the knee in full extension, the tibia reduced posteriorly and the Howell 65° tibial guide in place, a 2.4 millimetres guidewire was drilled through the central hole of the guide. After removing the guide, the wire position in the joint was first inspected visually and then the joint was disarticulated and the wire was hammered back so that its tip was flush with the tibial plateau. The tibial plateau was then photographed with a Nikon Coolpix 2.1 megapixel digital camera (Nikon Corporation, Tokyo, Japan) with a ruler positioned on the tibial plateau as a scale factor. A Steinmann pin was held in contact with the posterior aspect of the tibia and was assumed to be the posterior axis of the tibial plateau.

The pictures were downloaded to a personal computer and analysed with Microsoft Powerpoint 2002 software (Microsoft Corp). The pictures were normalised to a common scale and images of left knees reflected in order to all appear right-sided.

The distances of the ACL footprint and of the guidewire anteriorly from the “over the back” position were calculated. Their mediolateral positions were computed with respect to the lateral aspect of the medial tibial spine. Positions lateral to this axis were defined as positive, medial ones as negative (Fig. 7.5). The position of the border between the AM and PL bundle attachments along the medial and lateral aspects of the footprint was calculated.

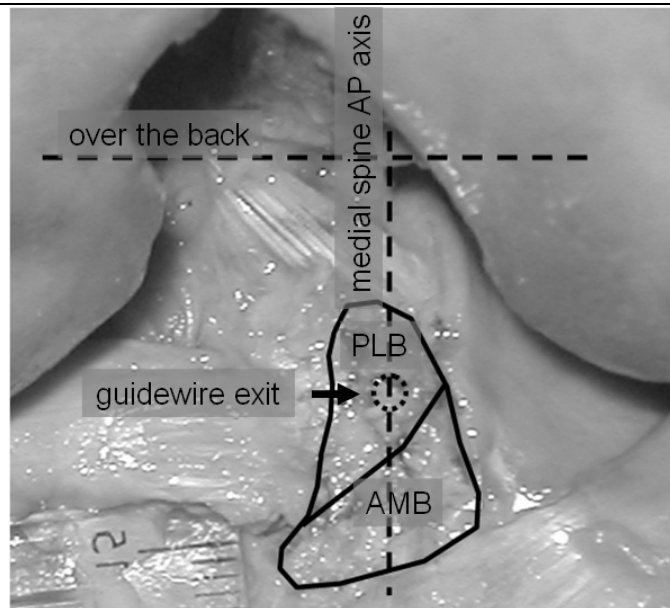


Figure 7.5: coordinate system to locate the guidewire exit within the tibial plateau. The ACL footprint is outlined and the longitudinal (passing through the medial spine) and posterior (over the back) axis are drawn (dotted lines).

The percentage position of the wire with respect to the attachment length and width was computed taking the posterior and medial borders to be the 0% positions in the sagittal and coronal planes respectively. A scatter plot of the wire position with respect to the footprint was obtained.

Because the ACL attachment was not aligned in an AP direction, the position of the wire within the attachment was recalculated in terms of an axis system aligned with the longest dimension of the attachment. A statistical analysis was performed with Windows Statistics 5.1 (StatSoft Inc., Tulsa, OK, USA) and Student's paired t-test was employed to compare the data obtained from the two axis systems.

7.3 Results

The anterior and posterior limits of the ACL attachment were at 22 mm (SD=3; range:16-27) and 6 mm (SD=2; range:2-8) respectively from the "over the back" position. The medial and lateral limits of the attachment were at -3 mm (SD=1;

range:-5 - -2) and 6 mm (SD=2; range:3-9) respectively lateral to the medial tibial spine. The tibial attachment was on average 17 mm long (SD=2; range:12-19) and 9 mm wide (SD=2; range:7-16). The border between the PL and AM attachments was at 11 mm (SD=2; range:8-14) on the medial side and at 17 mm (SD=4; range:11-24) on the lateral side from the "over the back" position. In percentage terms the medial border between the bundle attachments was at 33% (SD=12; range:12-58) of the footprint length while the lateral was at 68% (SD=14; range:47-94) (Fig. 7.6).

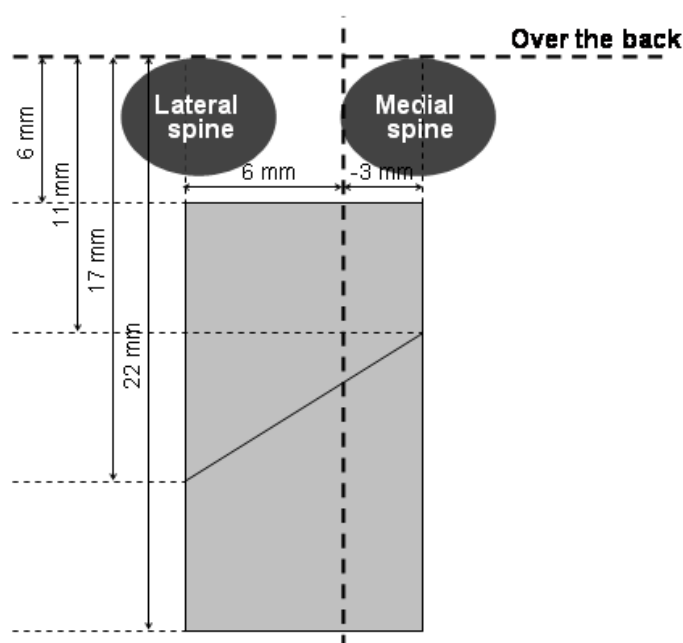


Figure 7.6: ACL attachment position. The slanting line is the boundary between the AMB and PLB.

The tip of the K-wire drilled through the 65° Howell tibial guide was in the PL bundle attachment in 17 knees and in the AM bundle attachment in 4 knees (Fig. 7.7). It was 12 mm (SD=3; range: 5-16) anterior to the over the back and 1 mm (SD=1; range:-3 - 2) lateral to the medial tibial spine. In one knee the wire was in a posterior position in the attachment; this could be explained by the relatively anterior position of the attachment itself, its posterior limit being 8 mm from the over the back.

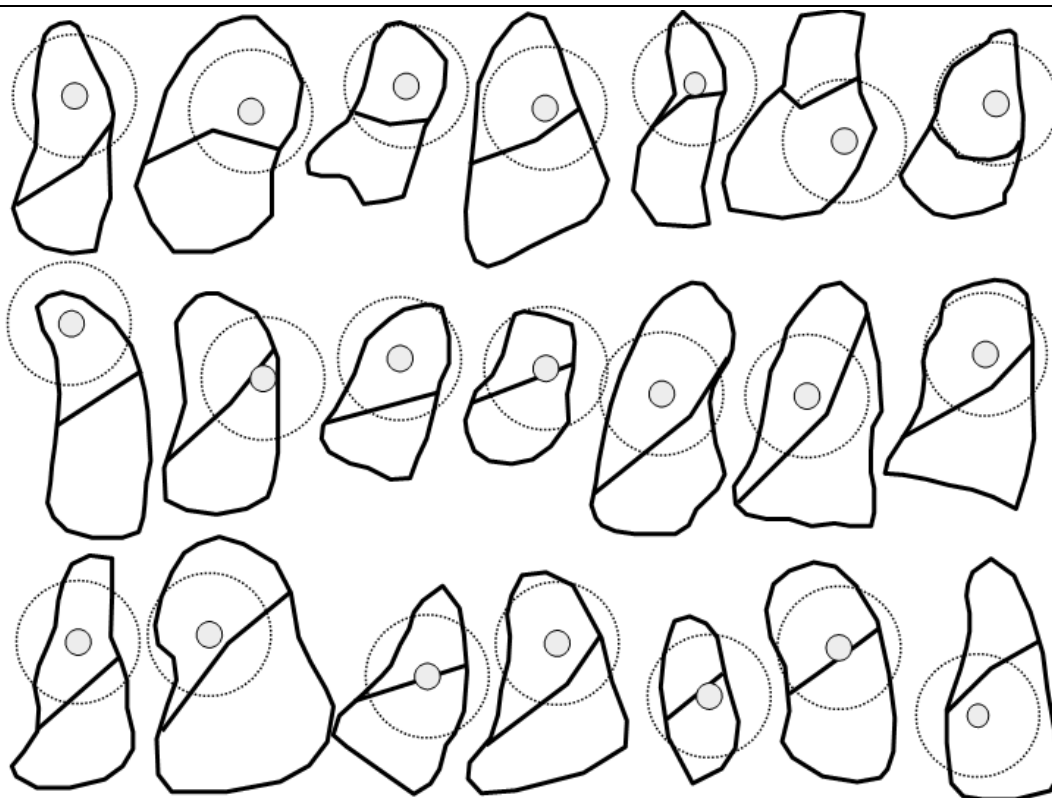


Figure 7.7: Normalised ACL attachments with the tip of the K-wire. The dashed circles indicate approximate tunnel openings with 9 mm drill. All diagrams represent the right knee, with lateral to the left and anterior to the bottom of the diagrams.

In percentage terms the tip of the wire was at 38% (SD=16, range:11-69) of the length and at 40% (SD=17; range: 14-75) of the width of the ACL attachment. A scatter plot of the percentage positions of the 21 wires in the 21 knees is shown in Fig. 7.8. When considering the long axis of the attachment, the wire was at 37% (SD=14; range:13-66) of the length and 48% (SD=17; range:10-70) of the width. The differences between the two axis systems were not significant: $p=0.5$ and 0.1 for length and width measurements, respectively.

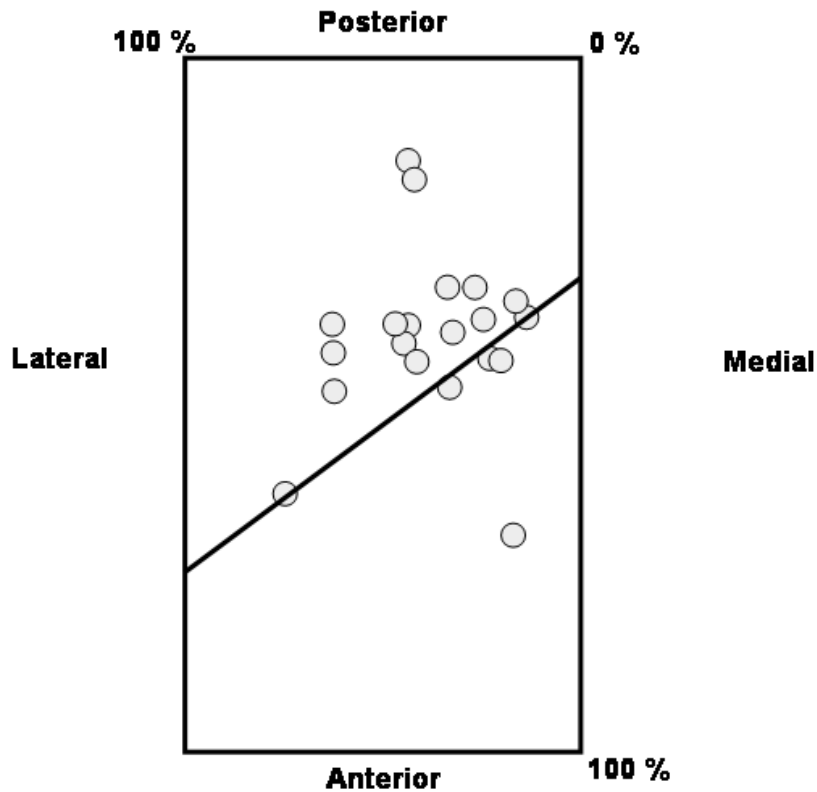


Figure 7.8: Scatter plot of the wire percentage position within the ACL footprint. Mean position: 38% of the length (SD 16%) and 40% of the width (SD 17%)

7.4 Discussion

The main finding of this study was that a guidewire drilled through the tibia with a 6 mm offset from the roof of the femoral intercondylar notch exited the tibial plateau within the anatomical ACL attachment in all twenty-one knees tested, thus confirming the hypothesis. It was within the attachment of the posterolateral bundle in seventeen of the twenty-one knees, the mean position being 38% (6.5 mm) from the posterior edge of the 17 mm long ACL attachment.

Anatomic placement of the tibial tunnel requires the tunnel to exit in the attachment area of the native ACL: the task of the surgeon is then to decide where to put an 8 to 10 mm tunnel in an area 17 mm long and 9 mm wide which may be difficult to identify arthroscopically. Many authors have tried to describe

the ideal tibial tunnel position. In the early 1980s the intraarticular exit of the tibial tunnel tended to be positioned slightly anterior to the centre of the natural ACL attachment, following the recommendation of Clancy, Nelson, Reider et al (1982) supporting anteromedial positioning to ensure graft isometry. This was not done with reference to the individual notch roof anatomy, and so the need for notchplasties (which is the removal of part of the notch roof to reduce graft impingement) was great.

Like the normal ligament, the anterior aspect of the graft should be parallel to the slope of the intercondylar roof with the knee in maximum extension. Placing the tibial tunnel in the anterior half of the ACL attachment may expose the anterior fibres of the graft to roof impingement (Howell 1998), because they go straight from the femur to the tibia, which is not anatomical. In contrast, the fibre architecture of the natural ACL leads to its anterior profile being concave. This means that fibres may reach areas in the anterior part of the tibial attachment that are not accessible by a straight graft without impingement.

MRI studies (Howell, Clark, Blasier 1992) have shown that an anterior tunnel resulted in graft-roof impingement with subsequent graft failure. The pathognomonic findings of this phenomenon included a signal increase in the distal two-thirds of the intraarticular portion of the graft and posterior bowing caused by contact with the intercondylar roof. Supporting this concept, Marzo, Bowen, Warren et al (1992) reported that anterior graft placement resulted in a fibrous nodule (cyclops) formation from partial graft rupture caused by graft impingement, leading to clinical mechanical symptoms like pain and loss of extension.

The evidence above suggests that it is acceptable to place the tibial tunnel for ACL reconstruction in the middle third of the original ACL attachment in the sagittal plane. A very posterior position on the tibia should be avoided because it is the least isometric, causing too much “elongation” toward extension (Penner, Daniel, Wood et al 1988; Sapega, Moyer, Scheneck et al 1990; Sidles, Larson, Garbini et al 1988). Furthermore, a posteriorly-placed tibial tunnel moves the graft towards a more vertically oriented proximal-distal orientation, and that is not efficient for withstanding anterior draw forces.

Khalfayan, Sharkey, Alexander et al (1996) reported that the optimal placement of the tibial tunnel is within 20% to 40% of the sagittal width of the tibia. Failure to achieve these radiographic parameters was correlated to considerably compromised clinical results. However, it is difficult to define the ideal anteroposterior position radiographically, and it would need intraoperative X-rays to confirm the absence of impingement. Furthermore, the intercondylar roof has an interindividual variability and impingement may still occur in the above-mentioned 20-40% safe area (Buzzi, Zaccherotti, Giron et al 1999).

Jackson and Gasser (1994) introduced anatomic landmarks in selecting the correct tunnel position. It was described as the mid-point of a line linking the inner or posterior edge of the anterior horn of the lateral meniscus and the medial spine and was consistently located 6 to 7 mm anterior to the anterior border of the PCL. In 1995 Morgan, Kalman and Grawl introduced a new tibial guide (Arthrex Inc, Naples, FL) using the PCL as a reference. The centre of the tunnel is 7 mm from the PCL with the knee at 90° flexion.

Given that the normal ACL lies against the intercondylar notch roof with the knee in maximum extension (Stäubli, Rausching 1994), it was thought that the intercondylar roof could be used as a rigid landmark to position a guide instead of relying on mutable, soft-tissue structures. Based on these observations Howell (Howell, Taylor 1993) designed a guide (One-Step, Impingement-Free Tibial guide, Arthrotek, Inc., Ontario, CA) that customizes the tibial tunnel in relation to the intercondylar roof. The efficacy of this guide in preventing roof impingement was validated with MRI and lateral radiographs of the extended knee (Howell, Barad 1995). The coronal angle was preset at 70°. In 2003 a new version of the guide was introduced: the 65° Howell Tibial Guide (Arthrotek, Inc., Ontario, CA). The latest edition is different from the first one in the 65° coronal angle and in a larger intra-articular probe. The 5° reduction in coronal plane angle was based on studies indicating that this would lead to better knee flexion (Simmons, Howell, Hull 2003; Howell, Gittins, Gottlieb et al 2001). This is the first study to validate in a cadaver knee the 65° Howell tibial guide.

These results show reproducibility in tibial tunnel placement. On average the tibial tunnel was at 38% of the anteroposterior length of the attachment and 80% of the

wires were between 35% and 48% of the footprint. All the wires but four were in the posterolateral bundle attachment and the most anterior of these was at 69% of the posteroanterior length of the footprint. Although in these four wires exited in the anterior half of the native ACL, this is not a concern because the tibial wire was drilled with the knee in full extension relying on a roof referencing guide, thus there is by definition no impingement. Although the intrarticular position should be safe, the authors recommend that the absence of graft impingement is always checked in extension after graft fixation. Some roof or lateral notchplasty may still be required because of the residual tibial mobility which may be present after reconstruction.

The importance of the medio-lateral position of the tibial tunnel has also been emphasised. Romano, Graf, Keene et al (1993) measured the medio-lateral placement in a radiographic study: tibial tunnel placement was significantly more medial in the patients who had flexion deficits. In this study, using the Howell tibial guide, the guide wire was at 40% of the mediolateral width of the ACL footprint, 1 mm lateral to the lateral aspect of the medial tibial spine. The new version of the guide has a larger probe which positions the wire centrally. Because the tibial guidewire is placed with the knee fully extended, which limits tibial rotation, the system reduces the possibility of medial-lateral errors.

In conclusion: this experience demonstrates the efficacy of a roof-referencing drill guide in positioning the ACL graft reproducibly in an anatomical position. Then this system can be extremely useful for those surgeons and researchers who are looking for an anatomic reconstruction. The system is finally suitable to be improved and employed in ACL DB reconstruction as it will be discussed in following chapters.

Chapter 8 – DB Tunnel Positioning with a Transtibial Approach

In Chapter 7 a commercially available guide (the One Step Howell guide), designed to drill the tibial tunnel with reference off the roof of the intercondylar notch, was validated and demonstrated that it could ensure anatomic tibial tunnel positioning within the attachment of the native ACL. In this chapter a prototype attachment to the Howell guide is presented. This was conceived to drill the posterolateral tibial tunnel in DB ACL reconstruction. Then a laboratory validation study of the new guide is presented with respect to the anatomic findings presented in Chapter 2.

8.1 Introduction

Despite the high rate of satisfactory results achieved with modern techniques in ACL reconstruction (Aglietti, Buzzi, Giron et al 1997; Aglietti, Giron, Buzzi et al 2004; Freedman, D'Amato, Nedeff et al 2003; Shelbourne, Gray 1997), some authors (Brandsson, Karlsson, Sward et al 2002; Bush-Joseph, Hurwitz, Patel et al 2001; Logan, Williams, Lavelle et al 2004; Ristanis, Giakas, Papageorgiou et al 2003; Tashman, Collon, Anderson et al 2004; Woo, Kanamori, Zeminski et al 2002) believe that SB ACL reconstruction does not restore the complexity of the native ACL which has two main functional components: AMB and PLB (Amis, Dawkins 1991; Gabriel, Wong, Woo et al 2004; Girgis, Marshall, Monajem 1975; Harner, Baek, Vogrin et al 1999; Kurosawa, Yamakoshi, Yasuda et al 1991; Norwood, Cross 1979) as it was also discussed in chapters 2 and 4.

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The purpose of ACL reconstruction is to restore stability to the knee, and this has traditionally been related to measurement of the reduction of anterior drawer in response to anterior tibial loads (Aglietti, Buzzi, Giron et al 1997; Aglietti, Giron, Buzzi et al 2004; Freedman, D'Amato, Nedeff et al 2003; Shelbourne, Gray 1997). Though successful in reducing the anterior drawer, several investigators have questioned the ability of single bundle reconstructions to control rotational laxity and avoid the pivot shift phenomenon (Brandsson, Karlsson, Sward et al 2002; Bush-Joseph, Hurwitz, Patel et al 2001; Logan, Williams, Lavelle et al 2004; Ristanis, Giakas, Papageorgiou et al 2003; Tashman, Collon, Anderson et al 2004; Woo, Kanamori, Zeminski et al 2002). Recent laboratory studies have confirmed these concerns (Brandsson, Karlsson, Sward et al 2002; Bush-Joseph, Hurwitz, Patel et al 2001; Logan, Williams, Lavelle et al 2004; Ristanis, Giakas, Papageorgiou et al 2003; Tashman, Collon, Anderson et al 2004; Woo, Kanamori, Zeminski et al 2002; Radford, Amis 1990; Yagi, Wong, Kanamori et al 2002; Yamamoto, Hsu, Woo et al 2004). All those investigators questioned the real effectiveness of the single bundle ACL reconstruction which recreates only the AMB. Furthermore in chapter 7 it was evident that a 9-mm tunnel covers less than half of the entire ACL attachment (Fig. 7.7).

Based on these findings it has been suggested that both the AMB and the PLB should be reconstructed. The PLB resists the majority of the anterior drawer force in the natural ACL (Woo, Kanamori, Zeminski et al 2002) and in ACL reconstructions (Yagi, Wong, Kanamori et al 2002) when the knee is nearly extended. Various techniques of double bundle reconstruction have been developed (Hara, Kubo, Suginoshita et al 2000; Mott 1983; Pederzini, Adriani, Botticella et al 2000; Zaricznyj 1987; Rosenberg, Graf 1994; Bellier, Christel, Colombet et al 2004; Marcacci, Molgora, Zaffagnini et al 2003; Takeuchi, Saito, Mituhashi et al 2002; Mae T, Shino K, Matsumoto et al 2010; Yasuda, Tanabe, Kondo et al 2010; Muneta, Koga, Mochizuki et al 2007; Fu, Shen, Starman et al 2008; Song EK, Oh LS, Gill et al 2009; Järvelä, Moisala, Sihvonen et al 2008) with promising preliminary results. However there is not yet a consensus on the proper tunnel positioning. It was hypothesized that a drill guide with two barrels, whose axes intersected at a known distance apart on the tibial plateau, could automatically place the two guidewires in the anatomical AMB and PLB femoral

and tibial attachments when the drill guide had been located against the roof of the femoral intercondylar notch in the extended knee.

The purpose of this study was to investigate on cadaver knees the ability of a surgical technique to place the graft tunnels within the anatomical attachments of the AMB and PLB on the femur and tibia, which was taken to be a condition for “anatomic” ACL reconstruction.

8.2 Materials and Methods

Twenty one fresh-frozen human cadaveric knees were used: they had been obtained with informed consent from relatives in accordance with a local research ethics committee permission and were thawed before testing. The specimens were prepared as described in Chapter 7.

The AMB and PLB were identified and separated as described in Chapter 3 and their tibial attachments demarcated. In order to properly identify and mark the femoral attachments of the bundles, the lateral femoral condyle was split from the medial condyle and from the diaphysis leaving it attached to the tibia through the lateral collateral ligament. After the demarcation of the femoral bundle attachments with red ink the condyle was reduced to its anatomic position and fixed to the medial condyle with screws. To optimally reduce the condyle a saw blade was left in the place of the sagittal bone cut in order to allow for the amount of bone removed by the saw blade. This procedure has no significant effect on the AP laxity of the knee (Zavras, Amis 1998). The femur was then secured in a 2 degree of freedom table vice which allowed knee flexion and extension. The posterior femoral condyles were aligned parallel to the floor.

Tibial part

21 knees were used in this study and prepared as described in Chapter 7. The Howell 65° tibial guide (Arthrotek Inc., Warsaw, IN , U.S.A.) was employed to drill the tibial tunnel according to the manufacturer's instructions (Chapter 7). To drill

the AMB tunnel the telescopic barrel was rotated 90° and the most anterior barrel hole was chosen (Fig. 8.1).

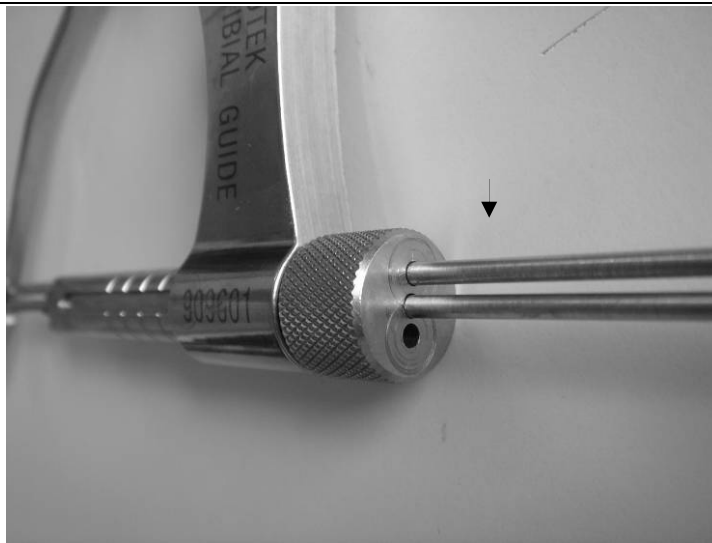


Figure 8.1: the guide barrel was rotated 90° and the AMB guide wire drilled through the most anterior hole (arrow)

When the guide wire was drilled into the joint, it knocked into the probe and a 3 mm space was left between the roof and the wire, avoiding roof impingement (Fig. 8.2). This offset should not expose the AMB graft to roof impingement as a smaller graft (6 mm) is used in double bundle reconstruction.



Figure 8.2: AMB guidewire (arrow) does not expose the AMB graft to roof impingement as a smaller graft (6 mm) is usually employed

To drill the PLB tibial tunnel a prototype attachment to the guide was employed (Fig. 8.3). The wire drilled through the attachment came into contact into the probe 6 mm posterior to the first one.



Figure 8.3: the 65°Howell tibial guide and the PLB attachment (arrow)

The PLB wire had a fixed coronal angulation of 20° with respect to the first one (Fig. 8.4). After a pilot study this was found to be the best configuration 1) to reach the PL femoral insertion through the tibia, 2) to leave a bony bridge of at least 1 cm between the two tunnels on the tibial cortex and 3) not to damage the medial collateral ligament.

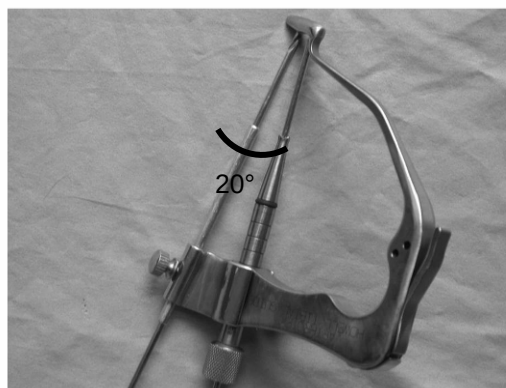


Figure 8.4: PLB guidewire has a 20° coronal angulation with the AMB

The experimental testing arrangement is shown in Fig. 8.5.

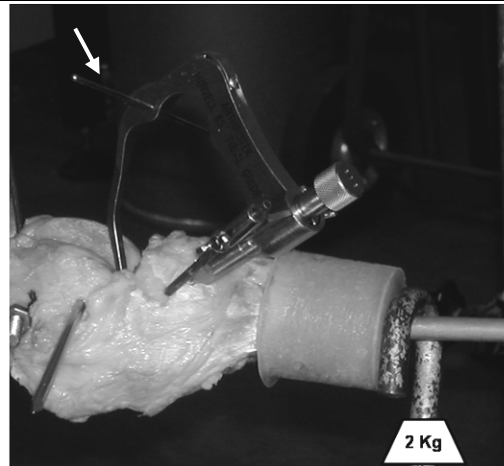


Fig 8.5: Testing conditions. The knee is in full extension, a rod is in the medullary canal and a 2 kg mass is hung from its proximal part. The 65° Howell guide and the attachment are in place. The red arrow indicates the 65° coronal alignment pin.

After removing the guide, the positions of the wires in the joint were first inspected visually and then the wires were hammered back so that their tips were flush with the tibial plateau. After completing the femoral part of the experiment the bones were separated and the tibial plateau was photographed with a Nikon Coolpix 775 digital camera (Nikon Corporation, Tokyo, Japan). A ruler was positioned on the tibial plateau as a scale factor. A Steinmann pin was held aligned with the posterior aspect of the tibia and was defined as the posterior axis of the tibia. This allowed the positions of the guidewires to be measured (Fig. 8.6).

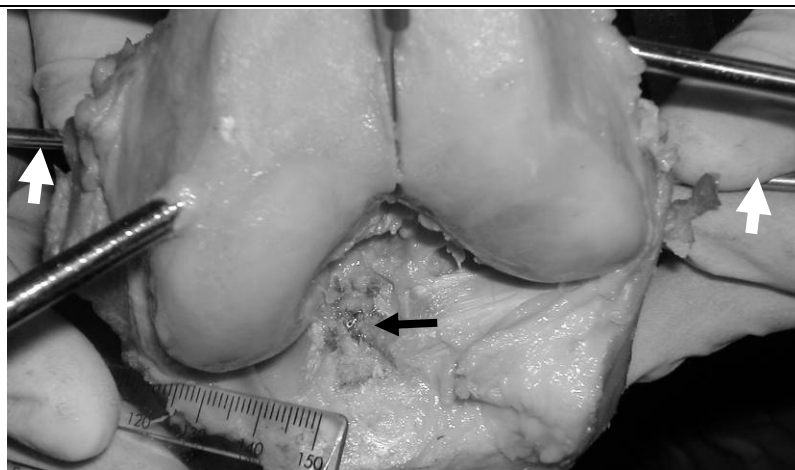


Figure 8.6: the tibial plateau is photographed after drilling the k-wires in the ACL footprint (black arrow). A Steinmann pin in contact with the posterior tibial plateau is the posterior axis (red arrows)

Femoral part

The femoral part of the study was performed in 14 knees; 7 knees were excluded due to abnormal mediolateral laxity in flexion. At 70° of knee flexion, manual maximum tibial external rotation and posterior drawer loads were applied. This load condition was chosen as, after preliminary trials on different specimens, it was found to be the one which allowed the femoral PLB attachment to be reached most easily through a transtibial approach (Fig. 8.7). In this position the PLB tibial wire was drilled across the joint space and through the lateral femoral condyle. Its tip was then pulled leaving the tail end flush with the notch wall. Up to date no surgical techniques had been demonstrated to be superior in replicating the native PLB femoral attachment. The experimental setting had the advantage of being constrained and was not surgeon-dependent.



Figure 8.7: tibia in posterior drawer and external rotation to allow to reach the femoral PLB attachment

A standard transtibial technique was employed to drill the AMB femoral tunnel. A 6 mm tibial tunnel was drilled over the AMB tibial wire. A femoral aimer with a 3 mm offset (Smith&Nephew, Memphis, MA) was introduced into the joint through the tibial tunnel and its tip was secured in the over the top (11 o'clock) position (Chapter 6 – Fig. 6.7). A wire was drilled through the aimer into the lateral femoral condyle and its tail was left flush with the wall.

The lateral femoral condyle was detached from the rest of the femur and the notch was photographed. Two pictures of the notch were obtained: one with the camera perpendicular to the ACL attachment in order to have the widest image of the attachment (attachment view), and one perpendicular to the femoral shaft in a medial-lateral direction (notch side view) (Fig. 8.8). A ruler was positioned on the femoral metaphysis as a scale factor.

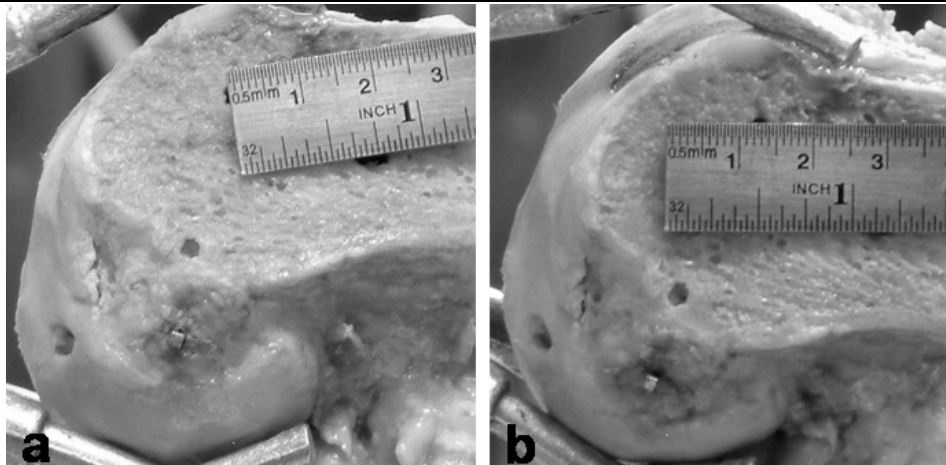


Figure 8.8: a) ACL attachment view; b) Medial-lateral view

Tibial data analysis

The pictures from all the plateaux were downloaded to a personal computer and analysed with Office XP Powerpoint software (Microsoft Corporation). All the images were normalised in size and mirrored, where appropriate, to be all right sided.

The position of the ACL attachment and of the two wires was described in the AP direction with respect to the over the back position (Hutchinson, Bae 2001) and in the medio-lateral direction relative the lateral aspect of the medial tibial spine. The positions lateral to this axis were assumed to be positive, the medial ones to be negative. The border between the AMB and PLB along the medial and lateral sides of the ACL attachment was also calculated. The wire positions were described as percentages of the attachment length and width with the posterior and medial aspects as 0%.

Femoral data analysis

All the pictures were scaled and right side normalised. The positions of the guide wires in the femoral side were described using an arthroscopic nomenclature as proposed by Zavras and Amis (1998 | Fig. 8.9).

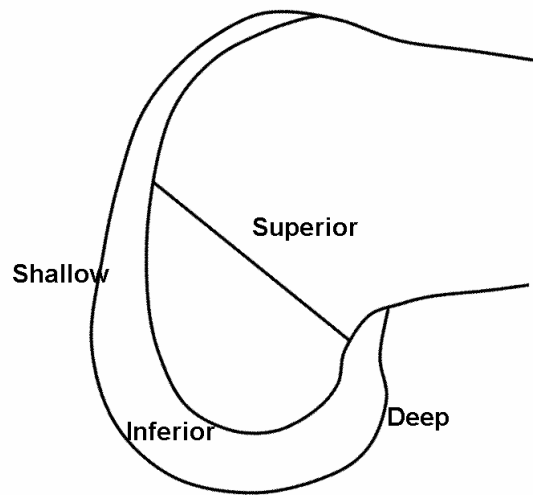


Figure 8.9: notch nomenclature according to Zavras and Amis (1998)

In the attachment view images, the dimensions of the attachment were calculated and the percentage positions of the wires with respect to the ACL attachment area computed. The superior and deep aspects of the attachment were defined as 100%, so that 100,100 was towards the “over the top position”.

In the notch side view the positions of the wires and of the centres of the AM and PL bundle attachments were measured according to the Zavras and Amis circle method (1998) defining the most inferior and shallow points of the circle as 0% and the most superior and deep as 100% with the shallow-deep axis parallel to the notch roof. A paired student t-test was performed to compare the positions of the wires and of the centres of the native ACL attachments.

8.3 Results

Tibia

As reported in Chapter 2, the anterior and posterior limits of the ACL attachment were at 22 mm (SD=3; range 16-27) and 6 mm (SD=2; range:2-8) respectively anterior from the over the back position. The medial and lateral limits of the attachment were at 3 mm (SD=1; range:2-5) medial and 6 mm (SD=2; range:3-9) lateral from the sagittal axis.

The tibial attachment was on average 17 mm long (SD=2; range:12-19) and 9 mm wide (SD=2; range:7-16). The border between the PLB and AMB attachments was at 11 mm(SD=2; range:8-14) on the medial side and at 17 mm (SD=4; range:11-24) on the lateral side from the 'over the back' position. In percentage terms the medial border between the bundle attachments was at 33%(SD=12; range:12-58) of the attachment length while the lateral was at 68%(SD=14; range:47-94).

After visual inspection, all 42 guidewires were within the ACL attachment: 17 of the 21 AMB wires were in the AMB attachment. The remaining 4 AMB wires were in the PLB attachment. Nineteen of the 21 PLB wires were in the PLB attachment, the remaining 2 were in the AMB attachment. In all cases the AMB and PLB wires in a correct relationship with one another, with the PLB posterior to the AMB (Fig. 8.10).

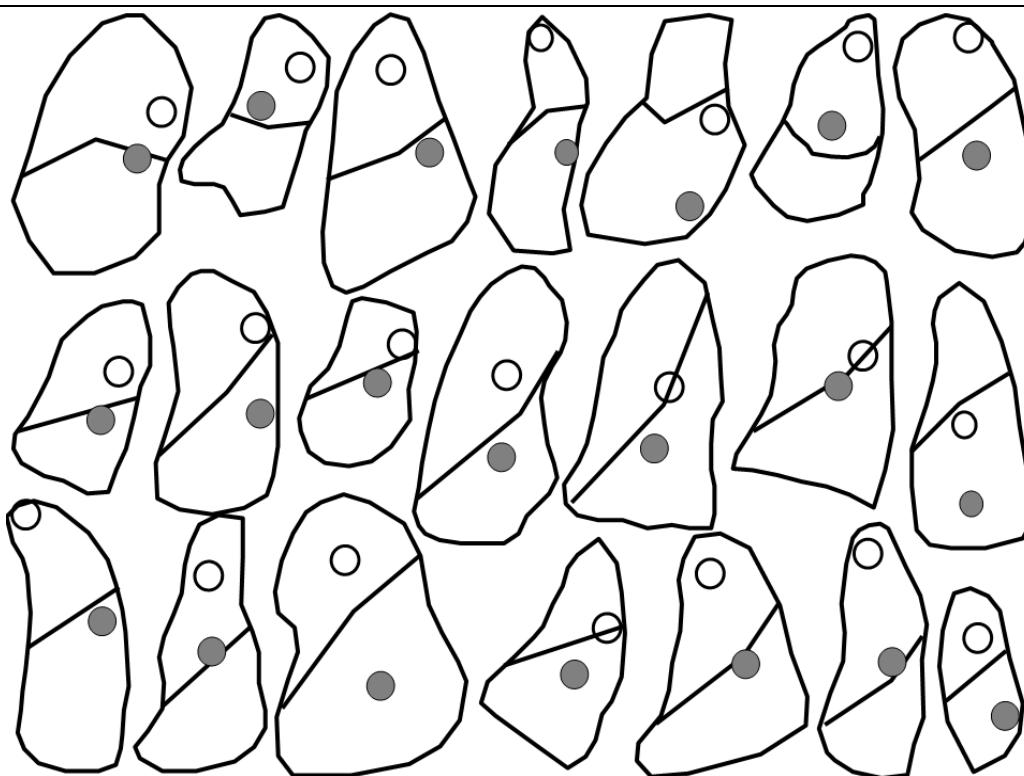


Figure 8.10: normalised and right sided ACL tibial attachments, split into AMB and PLB bundle attachments, with AMB (dot) and PLB (circle) wires in place

The AMB and PLB wires exited at 16 mm (SD=3; range:10-21) and at 10 mm (SD=1; range:4-15) respectively from the over the back position. Mediolaterally the AMB and PLB wires were at 0 mm (SD=3; range:-3 - -2) and 0 mm (SD=2; range:-3 - -3) from the sagittal axis at the lateral edge of the medial tibial spine. The average distance between the two wires was 5 mm (SD=2; range:3-11). This distance is close to the distance (6 mm) measured on the boom of the guide; the distance variation between the exit points of the two wires in different specimens is attributed to the variations in morphology of the tibial spines and ACL attachment, that could raise or lower the probe of the drill guide.

When considering the percentage position, the AMB and PLB wires were at 61% (SD=12; range:37-86) and 36% (SD=12; range:5-52) respectively of the posteroanterior length and at 36% (SD=12; range:11-62) and 37% (SD=20; range:9-66) respectively of the mediolateral width of the ACL attachment. A scatter plot of the 21 ACL attachments with the percentage wire positions is shown in Fig. 8.11.

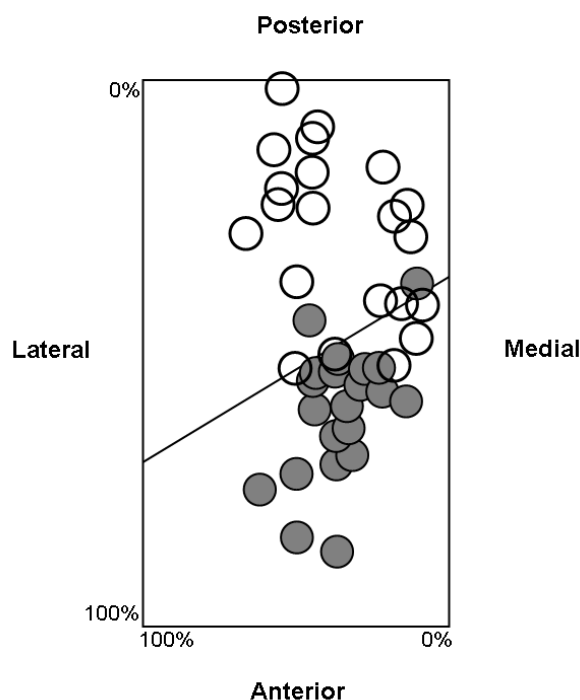


Figure 8.11: scatter plot of the 0-100% position of the AMB wire (dot) and the PLB wire (circle) within the tibial ACL attachment. The slanting line is the mean AMB-PLB boundary

Femur

As reported in Chapter 2 the ACL femoral attachment, measured in the attachment view, was 18 mm long (SD=2; range:14-22) and 9 mm wide (SD=1; range:8-11). The border between the AMB and the PLB attachments was at 46% (SD=12; range:27-64) of its shallow aspect and at 46%(SD=10, range:26-59) of the deep aspect. Twenty four of the 28 guidewires were within the ACL femoral attachment.

At visual inspection the AMB wire was in the AMB attachment in 12 of 14 knees, in the PLB attachment in 1 and shallow to the AMB attachment in 1 knee. The PLB wire was in the PLB attachment in 9 of the 14 knees, in the AMB in 2 and shallow to the PLB bundle in 3 (Fig. 8.12).

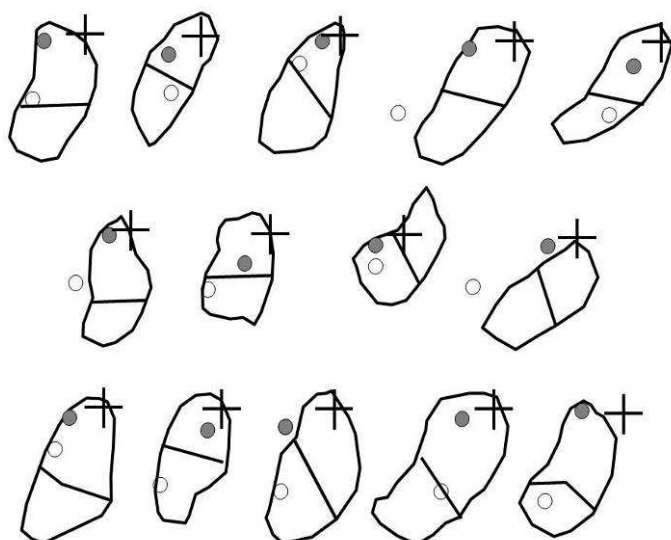


Figure 8.12: normalised and right sided ACL femoral attachments, split into AMB and PLB bundle attachments, with AMB (dot) and PLB (circle) wires in place. The cross indicates the “over the top”.

The AMB and PLB wires were at 76% (SD=15; range:40-92) and 32% (SD=17; range:10-60) below the superior margin of the ACL attachment respectively and at 24% (SD=19; range:-10-60) and 18% (SD=32; range:-40-70) shallow from the deep margin of the ACL attachment across its width (Fig. 8.13).

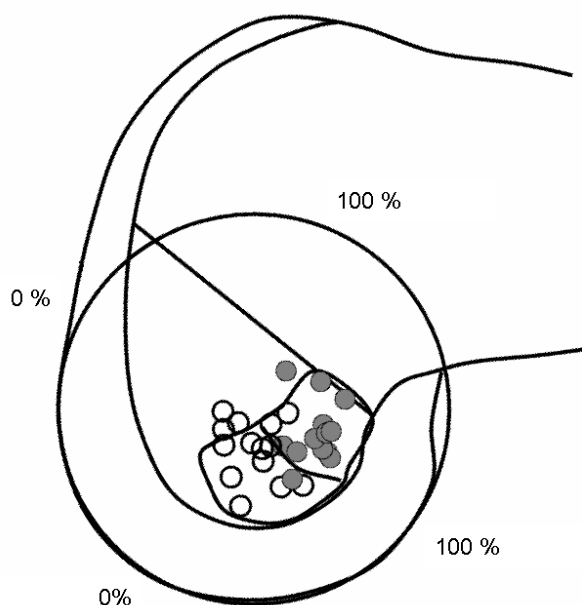


Figure 8.13: AMB (dot) and PLB (circle) wires position according to the circle method

The posterior part of the lateral femoral condyle fitted a circle with diameter 39 mm (SD=4; range:35-47); this was used as a normalising dimension (100%) according to Zavras and Amis (1998). The shallow-deep positions of the centre of the AMB attachment and of the AMB wire were 69% (SD=5; range:55-77) and 66% (SD=6; range:53-72) respectively ($p=0.03$). The infero-superior positions of the AMB centre and of the AMB wire were 50% (SD=7; range:34-59) and 56% (SD=8; range:41-73), respectively ($p<.001$).

The PLB attachment and the PLB wire were 61% (SD=4; range:53-67) and 57% (SD=7; range:49-71) deep respectively ($p=.026$). The infero-superior positions of the PLB attachment and the PLB wire were at 37%(SD=6; range:25-42) and at 43% (SD=8; range:28-60) of the circle height respectively ($p<.001$).

8.4 Discussion

This study has shown that a drill guide that was located against the roof of the femoral intercondylar notch with the knee extended, could control the positions of the guidewires for DB ACL reconstruction tunnels, so that they were positioned reproducibly with respect to the anatomical fibre bundle attachment. Because there are often no remnants of the native ACL in chronic cases, it is desirable to have instruments that relate to the remaining bony anatomy, that then guide the surgeon to the proper tunnel locations. This is the first experimental investigation of the ability of an ACL reconstruction technique to place tibial and femoral graft tunnels into the natural AMB and PLB attachments. Other authors have validated their own double bundle technique only in five femurs (Yasuda, Kondo, Ichiyama et al 2004). This ability is a key requirement for an “anatomical” double-bundle ACL reconstruction.

On the tibia all 42 guidewires were within the ACL attachment and only six of them not in the intended bundle attachment (Fig. 8.10). With a mean standard deviation of 2 mm in antero-posterior and medio-lateral positioning, the drill guide gave consistent results. In most knees the outline of a 6 mm tibial tunnel can be

expected to be partially out of the native bundle attachment. This must be ascribed to the interspecimen variability of the native ACL attachment shape, size and position. Furthermore the guiding system has been conceived to prevent graft impingement against the roof, thus resulting in a posteriorly biased tunnel position. Despite the fixed relationship between the two tibial wires on the guide boom (Fig. 8.3), the observed wire to wire distance variability can be explained with variable morphology of the tibial plateau surface. As a consequence, tunnel convergence can be expected in some knees. The clinical relevance of this finding cannot be predicted at the present time. Figure 8.10 also shows that some of the guidewires exited in the anterior part of the ACL attachment. This might cause concern regarding graft impingement against the roof of the femoral intercondylar notch, but it must be remembered that the drill guide was set-up to locate the guidewires at an offset away from the notch roof with the knee in full extension, so that all would have been impingement free. Some impingement may be theoretically be present as well due to physiologic anterior laxity under shear forces. These relatively anterior positions are impingement-free in a double-bundle reconstruction because the tunnels are smaller diameter than with a conventional "single bundle" technique.

The transtibial drilling technique was less accurate on the femur. That was expected, because the path of the guidewire across the joint space is dependent on the relative positions of the bones, and the exact posture of the ACL-deficient knee during surgery is affected by the forces imposed on it by hand. The best approach to replicate the native PLB attachment still needs to be defined. The transtibial technique was adopted as it is the easiest and more reproducible technique available giving the guidewire a fixed relationship to the femoral intercondylar notch in the extended knee. The AMB guide wire was inserted in a standard manner using a femoral aimer with a 3 mm offset. The PLB guide wire, conversely, was inserted through the tibia before drilling the tibial tunnel. This allowed the bones together to lock with the guide wire and to achieve a reproducible positioning in the absence of definite landmarks. Twenty-four of the 28 guidewires were located in the natural femoral attachment and 21 were in the intended AMB or PLB bundle attachment. There was a tendency for the wires to be placed high and shallow in the notch (i.e. antero-distal in anatomical

coordinates; Fig. 8.12 and 8.13). Given that the tibial exit points are fixed, correction of the femoral entry points for the guidewires depends on altering their orientations. It will be difficult to lower the femoral points, because that entails a shallower angle in the coronal plane, which might endanger the cartilage of the medial tibial plateau. There are several possibilities for obtaining greater accuracy on the femur: to alter the guidewire orientations of the drill guide or to use a separate femoral approach and jigs.

The principal weakness of this study is that it was based on cadaveric knees and not on live patients – the difference in operating conditions or tissue tone may have affected the tunnel positions achieved. It is known that removal of the extensor mechanism has no significant effect on AP laxity in vitro (Amis 1989; Shino, Inoue, Horibe et al 1987). Although it might have some effect on tibiofemoral position if the patellar tendon is tensed, this is not relevant to surgery under anaesthesia. The work was done in-vitro because that allowed accurate measurement of the centres of the natural ACL fibre bundle attachments, which is not possible clinically. The method of separating the femoral condyle, to allow true medial-lateral photography, is also known to not affect AP laxity significantly (Zavras, Amis 1998). Figures 8.10 and 8.12 shows that there was a variety of attachment site morphology encountered, so it would not be adequate simply to rely on mean data from prior studies, if any existed. This variability caused some of the guidewires not to be located in the intended fibre bundle attachment. This can affect knee biomechanics and the outcome of the reconstruction as the literature has shown that small changes in femoral tunnel position have very large effects on ACL graft length change patterns when the knee is moving (Zavras, Race, Amis 2005).

Although the previously described laboratory experience (Chapter 4) as well as the anatomical and biomechanical literature has shown clear roles for the AMB and PLB bundles of the ACL (Amis, Dawkins 1991; Gabriel, Wong, Woo et al 2004; Kurosawa, Yamakoshi, Yasuda et al 1991; Norwood, Cross 1979; Radford, Amis 1990; Yagi, Wong, Kanamori et al 2002; Yamamoto, Hsu, Woo et al 2004), no reconstruction methods (Hara, Kubo, Sugino et al 2000; Mott 1983; Pederzini, Adriani, Botticella et al 2000; Zaricznyj 1987; Rosenberg, Graf 1994; Bellier, Christel, Colombet et al 2004; Marcacci, Molgora, Zaffagnini et al 2003;

Takeuchi, Saito, Mituhashi et al 2002; Mae T, Shino K, Matsumoto et al 2010; Yasuda, Tanabe, Kondo et al 2010; Muneta, Koga, Mochizuki et al 2007; Fu, Shen, Starman et al 2008; Song EK, Oh LS, Gill et al 2009; Järvelä, Moisala, Sihvonen et al 2008)) have been validated for their ability to produce “anatomical” graft placements, with the tunnels in the intended AMB and PLB bundle attachments. Not all of these studies have included the four tunnels that should be considered necessary for a reconstruction to be “anatomic”. While the studies that have prospectively compared single- versus double-bundle ACL reconstructions (Hamada, Shino, Horibe et al 2001; Adachi, Ochi, Uchio et al 2004) have not shown any advantage for the double-bundle methods; this may have resulted from a lack of technical development of the surgical procedure, rather than an inherent lack of advantage of the double-bundle reconstructions. Relevant factors include the number of tunnels employed (only one tibial), tunnel positioning and graft tensioning protocols not matching the anatomy and function of the natural ACL.

This study has documented the tunnel positions achieved using one particular instrument, that locates on the femoral bony anatomy to guide the tunnel positions in the tibia, which lead transtibially to the locations on the femur. It is necessary to document technical details such as tunnel positioning if the pioneers of these novel reconstruction methods are to understand fully their results, so that there is a solid foundation on which to optimize future treatment of the ACL. It is concluded that the methods described in this paper achieved a reproducible and safe tibial tunnel positioning despite the high variability in ACL attachment morphology and position. On the femoral side modifications are needed and should be validated in order to be more anatomical especially for the PLB.

Therefore, in the next chapter a clinical study will be presented introducing at surgery the systems that we have validated in this chapter and in the previous one (Chapter 7).

Chapter 9 – SB vs DB reconstruction with different techniques

In Chapter 8, a DB ACL reconstruction surgical technique through a transtibial approach was presented and validated in cadaver knees resulting in accurate AMB tunnel positioning while the PLB was located quite superficial and high on the femoral wall. In this chapter a clinical study is presented. It compares SB ACL reconstruction to DB reconstruction performed with two different approaches on the femur: the transtibial and the outside-in.

9.1 Introduction

Despite intra-articular SB ACL reconstruction being recognised as the treatment of choice for symptomatic ACL insufficiency, recent large prospective series have failed to show full patient satisfaction and a complete return to the pre-injury activity level, independently from the graft and the surgical technique.

Objectively, in general, a satisfactory anteroposterior stability is restored but a residual rotational laxity has been reported and documented as a persistent positive pivot shift sign (Aglietti, Giron, Buzzi et al 2004; Daniel, Stone, Dobson et al 1994; Freedman, D'Amato, Nedeff et al 2003; Herrington, Wrapson, Matthews et al 2005; Kocher, Steadman, Briggs et al 2004; Pinczewski, Deehan, Salmon et al 2002; Shelbourne, Gray 1997; Spindler, Kuhn, Freedman et al 2004). In vivo kinematic investigations with various techniques have documented the inability of SB ACL reconstruction to restore intact knee rotational stability (Brandsson,

Karlsson, Sward et al 2002; Bush-Joseph, Hurwitz, Patel et al 2001; Logan, Williams, Lavelle et al 2004; Ristanis, Giakas, Papageorgiou et al 2003).

The relatively insufficient rotational control of traditional SB ACL reconstruction has been ascribed by some researchers to its inability to replicate the anatomy and the reciprocal tensional behaviour of the native ACL AMB and PLB (Amis, Dawkins 1991; Kurosawa, Yamakoshi, Yasuda et al 1991; Li, DeFrate, Sun et al 2004).

DB ACL reconstruction has been therefore advocated to more closely replicate the anatomy and function of the native ligament and to improve the rotational control (Mae, Shino, Miyama et al 2001; Radford, Amis 1990; Yagi, Wong, Kanamori et al 2002; Yamamoto, Hsu, Woo et al 2004). Several DB reconstruction techniques have been described with different approaches in particular on the femoral side (Bellier, Christel, Colombet et al 2004; Marcacci, Molgora, Zaffagnini et al 2003; Muneta T, Sekiya I, Yagishita et al 1999; Shino, Nakata, Nakamura et al 2005; Vidal, Brucker, Fu et al 2005; Yasuda, Kondo, Ichiyama et al 2004; Adachi, Ochi, Uchio et al 2004; Hamada, Shino, Horibe et al 2001; Järvelä 2007; Kondo, Yasuda, Azuma et al 2008; Muneta, Koga, Morito et al 2006; Siebold, Dehler, Ellert et al 2008; Streich, Friedrich, Gotterbarm et al 2008; Yagi, Kuroda, Nagamune et al 2007; Yasuda, Tanabe, Kondo et al 2010; Mae, Shino, Matsumoto et al 2010).

The aim of this study was to prospectively compare SB ACL reconstruction to DB ACL reconstruction after that in Chapter 2 AMB and PLB anatomy has been discussed and in Chapter 8 an anatomic DB surgical technique has been validated in cadavers.

9.2 *Materials and Methods*

This investigation was performed at the Department of Orthopaedics of the Careggi University Hospital in Florence, Italy.

After obtaining ethical approval by the specific hospital committee seventy-five fully consented patients with an isolated unilateral ACL tear were enrolled in the study. The first 25 patients (Group I) received SB transtibial ACL reconstruction. In the following 25 patients (Group II) DB single-incision transtibial ACL reconstruction was performed and the last 25 (Group III) underwent DB two-incision outside-in ACL reconstruction. Patients' demographics and history of trauma were comparable in the three groups (Tab. 9.1). In all the knees an autologous semitendinosus and gracilis tendon graft was used.

	Group I (n=25)	Group II (n=25)	Group III (n=25)
Age (years)	28±7 (17-40)	30±7 (15-39)	29±6 (16-38)
Male/female ratio	1.2 (14/11)	2.5 (18/7)	2.1(17/8)
Trauma (non contact / contact)			
Sport	16 / 5	12 / 8	14 / 6
Traffic	0 / 3	0 / 4	0 / 4
Work	1 / 0	0 / 1	0 / 1
Injury–surgery interval (months)	36±42 (3-132)	26±33 (3-132)	23±29 (4-60)

Table 9.1: patients demographics were comparable in the three groups

Surgical technique

All the procedures were performed by a senior and experienced surgeon with the use of a tourniquet. Complete ACL tear was confirmed at arthroscopy. Semitendinosus and gracilis tendons were harvested with a smooth tendon stripper (Linvatec, Largo, FL) through a longitudinal approach medial to the tibial tubercle.

Tibial tunnels

In Group I the tibial guidewire was drilled with the Howell 65° Tibial Guide (Arthrotek, Warsaw, ID, USA) according to the manufacturer instructions (Chapter 7).

In Group II and Group III two tibial tunnels were drilled in the same fashion. The AMB guidewire was drilled through the Howell 65° Tibial Guide anterior hole after that the guide barrel was rotated 90°. This positioning does not expose the AMB bundle graft to roof impingement as usually a 6.0 millimeter tunnel is produced (Chapter 7,8). The PLB guidewire was drilled through a prototype attachment to the Howell 65° Guide. This setup has been demonstrated in the cadaver to be accurate and reproducible in replicating native bundles attachments in the tibia (Chapter 8). An arthroscopic view of the two tibial tunnels is shown in Fig. 9.1.

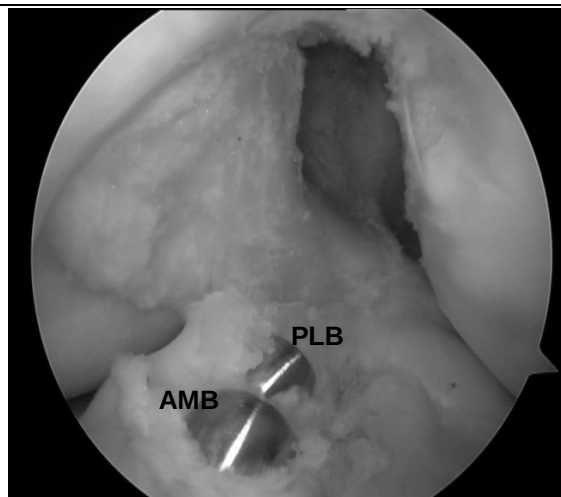


Figure 9.1: AMB and PLB tunnels drilled through the Howell guide and its attachment

Femoral tunnels

In Group I the femoral guidewire was drilled at 70°-80° of knee joint flexion through the tibia with a 5 mm offset femoral aimer which refers off the “over the top” position. A more inferior and deep position in the wall was achieved by externally rotating the aimer (Fig. 9.2).

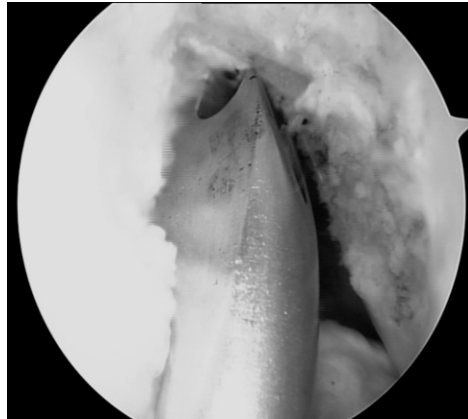


Figure 9.2: 5 mm offset femoral aimer hooked in the over the top position

In Group II a graft size specific AM tunnel was drilled through the tibia in the same fashion of Group I. The PL tunnel was drilled through the tibia with zero offset aimer at 70° of knee joint flexion with the knee in external rotation and posterior drawer (Fig. 9.3). This loading condition was found in the cadaver to be the most accurate to replicate the PLB bundle native insertion (Chapter 8).

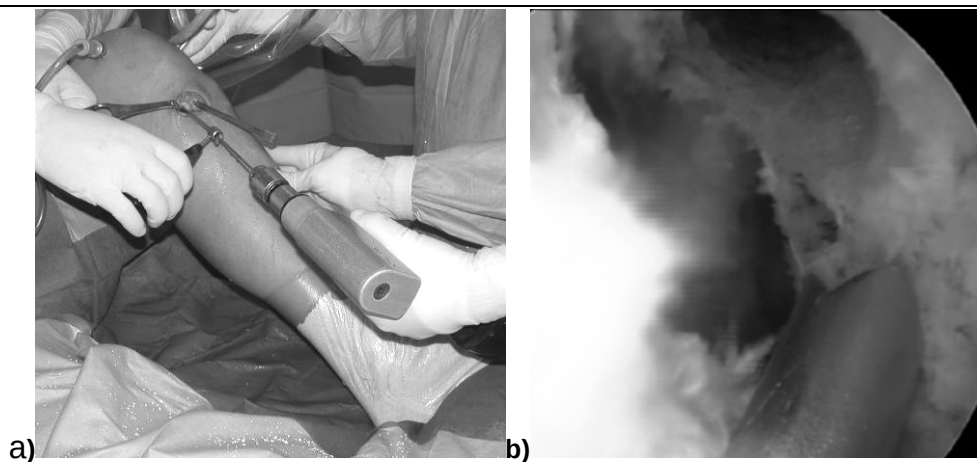


**Figure 9.3: a) knee at 70° of flexion in external rotation and posterior drawer;
b) arthroscopic view of the femoral aimer to drill the PLB guidewire**

Figure 9.4 shows the AMB and PLB tunnels drilled through the transtibial approach.

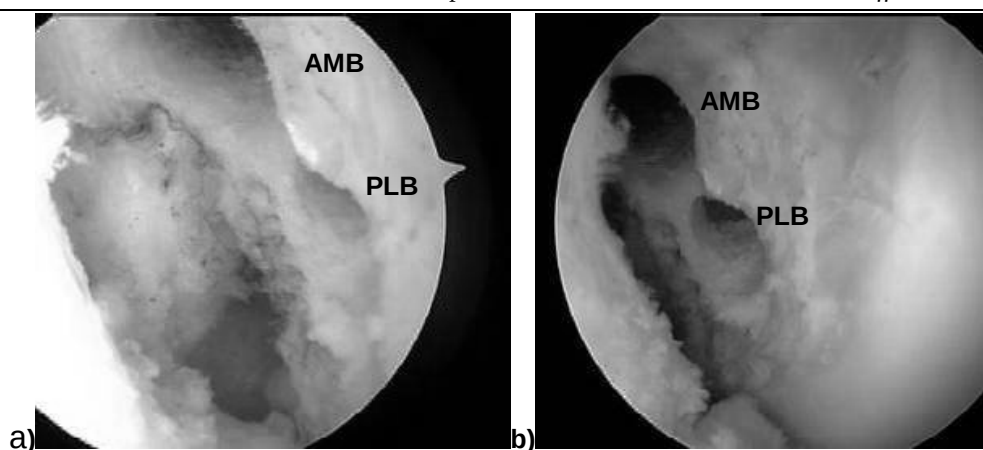


Figure 9.4: AMB and PLB femoral tunnels visualised through the a) anterolateral and the b) anteromedial portal

In Group III the femoral tunnels were drilled outside-in through an additional short lateral approach to the distal femur. The AMB guidewire was drilled as deep as possible on the lateral wall close to the “over the top” position with the Rear Entry guide (Acufex Microsurgical Inc., Mansfield, MA, USA) while the wall was visualised through the anteromedial portal (Fig. 9.5).

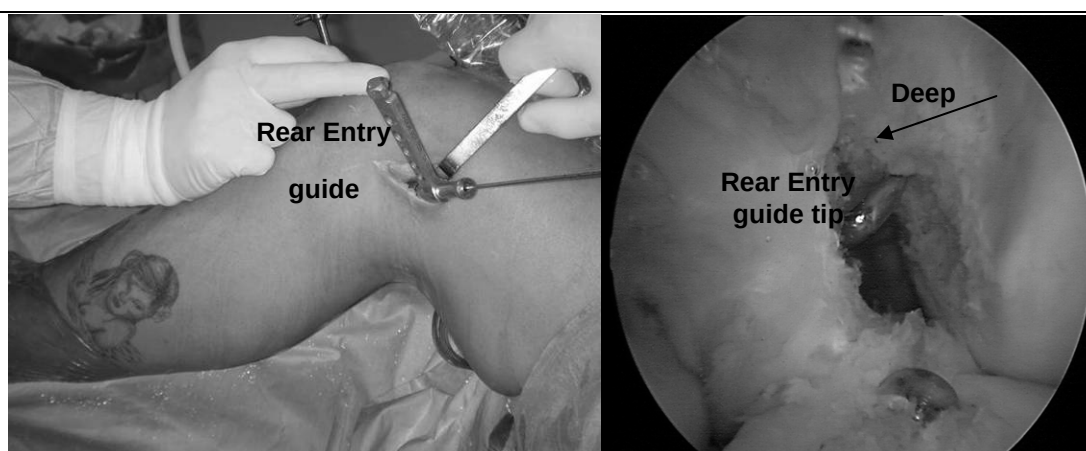


Figure 9.5: a) Rear Entry guide in place to drill the AMB tunnel b) arthroscopic view

The PLB wire was drilled outside-in 9 mm more shallow and inferior than the AM wire and close to the cartilage border employing a prototype guide which was inserted on the AMB guidewire (Fig. 9.6).

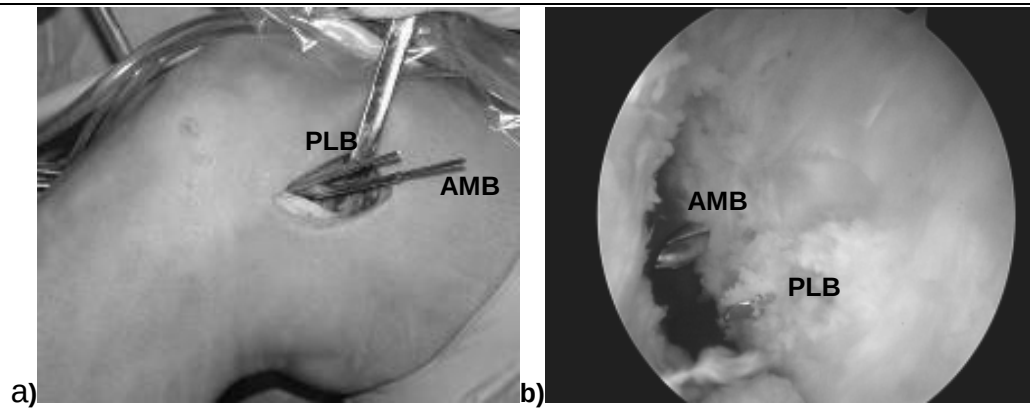


**Figure 9.6: a) PLB prototype attachment to AMB guidewire;
b) arthroscopic view of the two guidewires**

A bony bridge between the two tunnels was always present (Fig. 9.7).

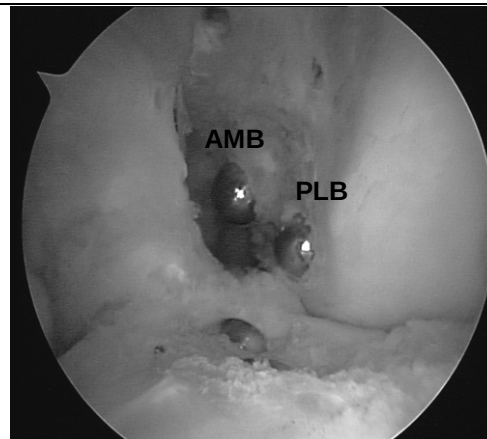


Figure 9.7: AMB and PLB femoral tunnels drilled through the outside-in approach

Graft passage and fixation

In Group I a doubled semitendinosus and gracilis graft was passed in the joint and secured on the femur with an Endobutton CL (Acufex Microsurgical Inc. MA USA). Final tibial fixation was achieved with a Washerloc (Arthrotek, Warsaw, ID, USA) at 10° of knee joint flexion after cycling under a manual tension of approximately 40 N.

In Group II and Group III the PLB and AMB grafts were separately fixed at 10° and 50° of flexion respectively, after cycling under a manual tension of

approximately 20 N each. In group II a doubled gracilis graft and a doubled semitendinosus graft reconstructed the PLB and AMB bundles. Femoral fixation of each bundle was achieved with an Endobutton CL. On the tibia the PLB graft was first temporarily secured near extension (10°) with a staple and then a Washerloc fixed the AMB graft and again the PLB graft in flexion (45°).

In Group III a single semitendinosus and gracilis tendon graft was looped around the tibial bony bridge between the two tibial tunnels exits and the free ends exited the femoral cortex. First PLB graft fixation was achieved at 10° of flexion, with one 6 mm RCI screw in the femur and one on the tibia. AMB graft femoral fixation was obtained through one 6 mm RCI screw while its tibial fixation relied on the tibial bony bridge and the previously introduced RCI screw. A final staple securely fixed both grafts to the lateral femoral cortex.

A schematic representation of the fixation in the three groups is shown in Fig. 9.8.

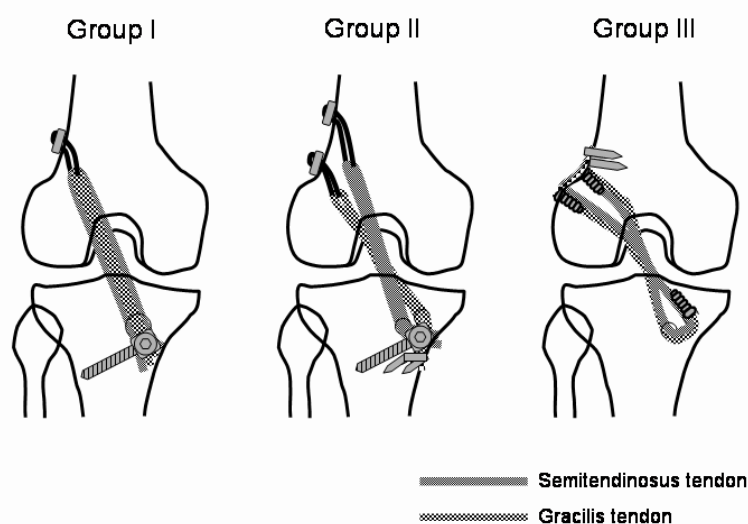


Figure 9.8: schematic representation of the surgical technique in the three groups

Meniscal pathology included 9, 8 and 9 medial meniscus and 2, 1 and 6 lateral meniscus lesions in groups I, II and III respectively. 2 and 3 medial meniscus lesions were sutured in Group I and Group II respectively. A limited partial meniscectomy was performed in all the other cases.

Postoperative rehabilitation

A brace-free rehabilitation protocol was adopted in all the groups (Aglietti, Giron, Buzzi et al 2004). Full range of motion and full strength were recovered after four and eight weeks respectively. Running was allowed after 3 months and return to sports-specific training after 4 months.

Magnetic Resonance Study

Fifteen consecutive patients in Group II and Group III underwent 4 months after surgery a magnetic resonance study to document AMB and PLB femoral tunnel position. The index knee was studied with a 1.5 Tesla Siemens MRI scanner. The MRI images were downloaded on a personal computer and the intercondylar roof aligned as horizontal. The MRI volume was adjusted so that sagittal slices were parallel to the lateral wall of the notch (i.e. medial aspect of the lateral femoral condyle): this resulted in wall pictures comparable in orientation to those obtained in the cadaver study described in Chapter 8. Then the slice showing the lateral femoral condyle largest anteroposterior width was chosen and the posterior aspect of the condyle was fit to a circle according to the Amis circle method (Zavras, Amis 1998, Chapters 2 and 8). Finally the circle was pasted on the slice showing the intra-articular tunnel exits and their position was calculated as shown in Chapter 8 on cadaver knees (Fig. 9.9).

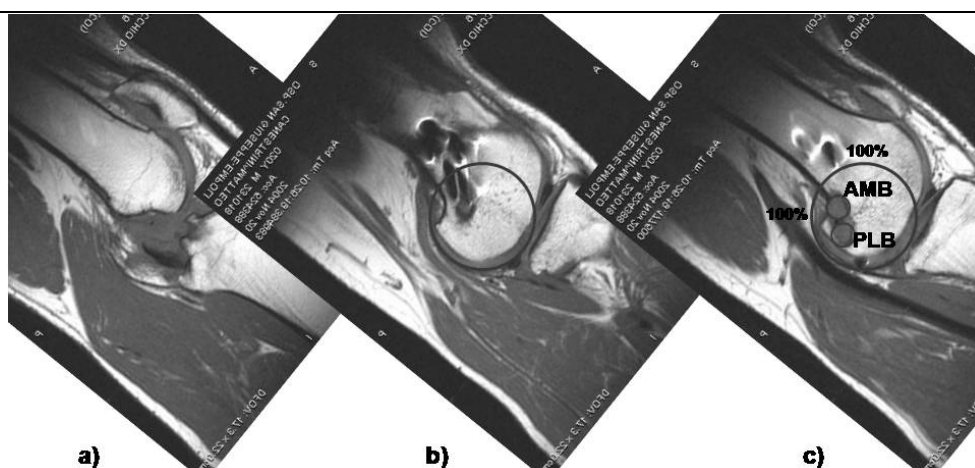


Figure 9.9: a) MR images were rotated with the intercondylar roof aligned as horizontal;
 b) the Amis circle was fit to the posterior lateral femoral condyle contour;
 c) AMB (green) and PLB (red) intra-articular tunnel exit coordinates were calculated

Clinical evaluation

All the patients were evaluated before surgery, every 2 weeks up to the second postoperative month,; monthly up to 4 months after surgery, and then at one year thereafter by an independent and blinded observer. At each control both knees of the patients were covered with a stockinette in order to hide the operated side and the skin incisions employed. Subjective and objective examination was performed in accordance to the Knee Injury and Osteoarthritis Outcome (KOOS) Score (Roos, Roos, Lohmander et al 1998) and to the International Knee Documentation Committee (IKDC) evaluation form (Irrgang, Anderson, Boland et al 2001). Side to side difference in anterior tibial translation was assessed with the knee flexed 30° using the KT-1000 arthrometer (Medmetric, San Diego, California) at 133-N and manual maximum forces.

Statistical Analysis

All statistical analyses were conducted on Stat Win II software (StatSoft, Tulsa, OK, USA). Comparison of the differences between groups was made with the Student t-test for continuous variables and with the Chi-square test and Fisher's exact test for categorical variables. In all tests, an alpha level of 0.05 was considered significant.

9.3 Results

Magnetic Resonance study

In Group II the AMB tunnel exit was at 56% (SD=6; range: 48-69) of the infero-superior circle height and at 65% (SD=5; range: 53-73) of the width. The PLB tunnel was at 40% (SD=6; range: 30-48) and 54% (SD=7; range:46-67) of the height and width respectively (Fig. 9.10).

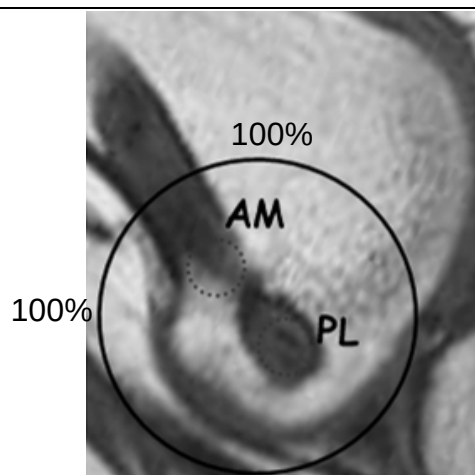


Figure 9.10: MR image showing tunnel positioning in one knee from Group II

In Group III the AMB tunnel exit was at 48% (SD=5; range: 40-59) of the infero-superior circle height and at 66% (SD=5; range: 58-75) of the width. The PLB tunnel was at 32% (SD=5; range: 17-40) and 57% (SD=7; range:40-68) of the height and width respectively (Fig. 9.11).

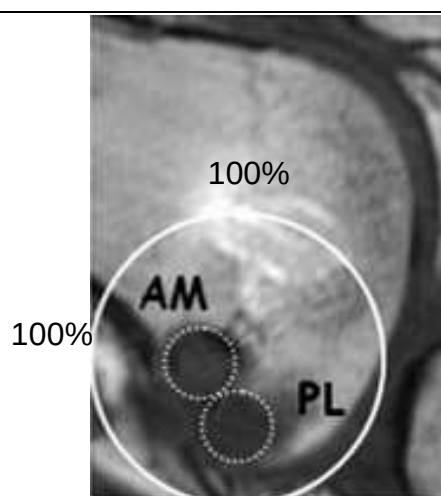


Figure 9.11: MR image showing tunnel positioning in one knee from group III

Clinical Results

All the patients had 1 year minimum follow-up. Four failures were recorded in this series. One patient in group I and one patient in Group III re-injured during resumed sports activities. In addition one failure in Group I and one in Group II

had not a traumatic origin. Only one knee so far has been revised after one year (Fig. 9.12).

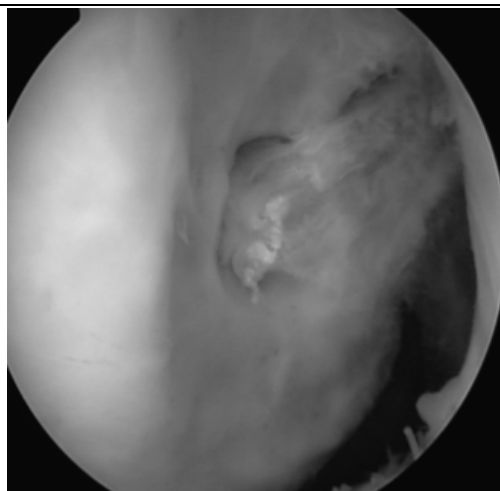


Figure 9.12: non traumatic failure in Group II that can be probably explained with the shallow and superior PLB tunnel positioning

After one year the IKDC subjective score in Group I, Group II and Group III were 72, 80 and 85 respectively ($p < 0.05$ comparing group I and III). Subjective KOOS scores are summarised in Tab 9.2.

	Group I	Group II	Group III
Pain	89±11	92±8	90 ±9
Symptoms	87±11	88±7	88±7
ADL	98±4	96±8	99 ±2
Sports activities	78±20	80±22	88 ±11
Quality of life	67±23	72±23	82 ±17 [†]

Table 9.2: one year KOOS scores. † Statistically significant compared to Group I ($p < 0.05$)

Objectively none of the patients in this series had persistent joint effusion. Only one patient (Group I) had a flexion deficit of 15°. Anteroposterior knee stability was considered normal in 58%, 64% and 80% of the patients in Group I, Group II and Group III, respectively. KT side to side difference at 134 N was 2.3, 1.8 and 1.2 mm ($p < 0.05$ comparing group III to group I) in group I, II and III,

respectively. 58%, 76% and 84% of the patients had a negative pivot shift in group I, II and III respectively ($p<.05$ comparing group III to group I). One year stability results according to the IKDC form and KT values with relevant statistics are summarized in Tab. 9.3.

	Group I (n=25)	Group II (n=25)	Group III (n=25)
Kt-1000 ssd at 30lbs			
0-2 mm	14 (58%)	16 (64%)	20 (80%)
3-5 mm	8 (34%)	8 (32%)	4 (16%)
> 6 mm	2 (8%)	1(4%)	1 (4%)
Pivot shift test			
Absent	14 (58%)	19 (76%)	21 (84%) [†]
Glide	8 (34%)	5 (20%)	3 (12%)
Clunk	2 (8%)	1(4%)	1 (4%)

Table 9.3: 1-year stability results. † Statistically significant compared to group I ($p=.04$)

Overall objective IKDC categories in group I, II and III were: A in 58%, 72% and 80%; B in 34%, 24% and 16%; D in 8%, 4% and 4% of the patients, respectively.

In summary, Group III patients were significantly more satisfied of the operation than patient in Group I and Group II according to IKDC score ($p<.05$). KOOS scores revealed that patients in Group III have a significantly better quality of life than patients in Group I ($p<.05$). Objectively KT measurements showed that knees in Group III are significantly more stable than Group I ($p=.04$). A significant less pivot shift in Group III than Group I was observed ($p=.04$)

9.4 Discussion

The main finding of this investigation is that a DB ACL reconstruction, particularly when performed with two incisions and outside-in femoral tunnels, resulted in greater patients' satisfaction and better anteroposterior stability than SB ACL reconstruction. A trend towards less residual pivot shift was also observed.

DB ACL reconstruction has been introduced to improve the already good, but not fully satisfactory, subjective and objective results currently achieved with SB ACL reconstruction. After SB reconstruction, in fact, up to one fifth of the patients do not resume pre-injury sports activities and usually complain of vague instability symptoms that objectively correspond to a mild persistent positive pivot shift sign (Aglietti, Giron, Buzzi et al 2004; Freedman, D'Amato, Nedeff et al 2003; Kocher, Steadman, Briggs et al 2004; Pinczewski, Deehan, Salmon et al 2002). Furthermore SB reconstruction does not seem to prevent the progression of osteoarthritis (Fithian, Paxton, Stone et al 2005; Hogervost, Pels Rijcken, Rucker et al 2002; Pinczewski, Deehan, Salmon et al 2002).

In vivo kinematics studies have confirmed the poor rotational control of SB ACL reconstruction, especially towards extension, with a persistent tibial internal rotation similar to the ACL deficient knee condition rotations (Brandsson, Karlsson, Sward et al 2002; Bush-Joseph, Hurwitz, Patel et al 2001; Logan, Williams, Lavelle et al 2004; Ristanis, Giakas, Papageorgiou et al 2003; Tashman, Collon, Anderson et al 2004). This insufficient rotational control can be ascribed to the spatial orientation of a central and vertical graft in the notch capable to resist anteroposterior forces but not rotational stresses. Even a more horizontal orientation of the graft obtained through a lower femoral entry point does not completely restore intact knee rotational laxity, particularly in flexion (Loh, Fukuda, Tsuda et al 2003).

Intact knee combined anteroposterior and rotational stability is indeed provided by the distinctive multiplanar configuration of the native ACL consisting of a continuum of variously oriented fibers which are differently recruited through range of motion. Agreement exists that two main functional bundles can be identified: the AMB, which is the most isometric, and the PLB which is more laterally placed and more taut towards extension (Amis, Dawkins 1991; Bach, Hull, Patterson 1997; Gabriel, Wong, Woo et al 2004; Girgis, Marshall, Monajem 1975; Harner, Baek, Vogrin et al 1999; Kurosawa, Yamakoshi, Yasuda et al 1991; Li, DeFrate, Sun et al 2004; Sakane, Fox, Woo et al 1997).

DB ACL reconstruction has been so conceived to replicate native ACL anatomy and possibly improve rotational stability. In vitro kinematics investigations performed with various techniques have demonstrated the superiority of DB reconstruction in restoring rotational control (Mae, Shino, Miyama et al 2001; Radford, Amis 1990; Sbihi, Franceschi, Christel et al 2004; Yagi, Wong, Kanamori et al 2004; Yamamoto, Hsu, Woo et al 2004). Various DB ACL reconstruction techniques have been so far described (Bellier, Christel, Colombet et al 2004; Marcacci, Molgora, Zaffagnini et al 2003; Muneta, Sekiya, Yagishita et al 1999; Shino, Nakata, Nakamura et al 2005; Vidal, Brucker, Fu 2005; Yasuda, Kondo, Ichiyama et al 2004). On the other hand two early short-term comparative clinical studies (Adachi, Ochi, Uchio et al 2004; Hamada, Shino, Horibe et al 2001) failed so far to demonstrate a clear advantage in using a DB graft especially in terms of rotational stability. Both studies anyway employed only one single tibial tunnel.

This is the first study to compare two different DB reconstruction techniques to SB reconstruction. Besides roof and PCL impingement avoidance, prerequisite of a DB reconstruction technique should be the close replication of native bundle attachment sites. Two tibial tunnels were also drilled as well in both DB groups.

The superior results achieved in this series by the two incision DB technique can be attributed to the more anatomical femoral tunnel positioning. Several Authors have demonstrated that single incision techniques are not always anatomic (Arnold, Kooloos, van Kampen et al 1999, Giron, Buzzi, Aglietti

1999). In the cadaveric validation of the single incision DB technique (Chapter 8) a tendency was found for the tunnels, especially the PLB, to be superior and shallow in the notch, thus causing the PLB graft to become taut in flexion. This tendency was confirmed also in vivo in the MRI study. Furthermore the failure which was observed in Group II could be ascribed to femoral tunnel malpositioning (Fig. 9.12).

Outside-in jigs on the contrary are less constrained and allow the replication of native bundle attachments. As confirmed by the MRI study the outside-in technique allowed a deeper and more inferior tunnel particularly with the PLB tunnel and closer to the position observed in cadaver knees (chapters 2,8). The knowledge of native ACL anatomy and the understanding of the correct tunnel positioning remains critical and makes this technique demanding as no definitive landmarks have been described so far.

One further point of discussion is soft tissue graft fixation. Endobutton CL fixation as in Group I and Group II has a construct stiffness well below that of the STG graft themselves as well as that of the intact ACL (Kousa, Jarvinen, Vihavainen et al 2003). Furthermore graft-tunnel motion (longitudinal and transverse motion) is much less using interference screw when compared to Endobutton CL (Tsuda, Fukuda, Loh et al 2002). The adjunct of a cortical staple anyway improves the fixation, particularly in women (Hill, Russell, Salmon et al 2005).

Despite improved anteroposterior stability the DB reconstruction in this study did not show a clear advantage in terms of rotational control. A trend towards less incidence of pivot shift was observed in Group III. Pivot shift grade has been found to be the best objective indicator of patients' satisfaction (Kocher, Steadman, Briggs et al 2004). Unfortunately pivot shift testing and grading are extremely examiner dependent and in vivo outpatients instrumented objective tools are still not available.

The main limitation of this study is that it was a not randomized preliminary study. As a consequence the three groups were not comparable in all the preoperative assessed data. More females and more patients with a chronic

lesions were observed in group I. Therefore in next chapter a longer follow-up prospective strictly randomized clinical trial will be presented. Furthermore only two femoral approaches were compared. The transportal approach was deliberately excluded due to its technical difficulties described in Chapter 6 (i.e. poor visualization in deep flexion, risk of cartilage damage, tunnel length and orientation).

In conclusion DB ACL reconstruction is an appealing technique and its theoretical advantages over SB reconstruction have been clearly demonstrated. This short-term experience with DB reconstruction suggests that better clinical results might be able to be achieved with the double incision technique which allows a more anatomical tunnel placement. In vivo equipments are needed to precisely and objectively assess knee rotational stability.

Chapter 10 – SB vs DB outside-in ACL reconstruction

In Chapter 9, a Level II study was presented, comparing single-incision and double-incision DB to single-incision SB ACL reconstruction and it was found that only double-incision DB reconstruction performed better than SB. In this chapter a new Level-I clinical study will be presented to compare double-incision DB to double-incision SB to test whether a more anatomic SB technique is sufficient for restoring knee laxity or if a DB reconstruction is truly needed.

10.1 Introduction

DB ACL reconstruction is increasing in popularity with the aim to reproduce native ACL anatomy and improve ACL reconstruction outcome. In particular, DB supporters aim at improving anterior and rotational knee stability and increasing knee function.

Controlled laboratory studies (Mae, Shino, Miyama et al 2001; Radford, Amis 1990; Yagi, Wong, Kanamori et al 2002; Yamamoto, Hsu, Woo et al 2004) have shown the superiority of DB ACL reconstruction in restoring intact knee kinematics, including translations and rotations. On the other hand, short-term comparative clinical trials (Adachi, Ochi, Uchio et al 2004; Aglietti, Giron, Cuomo et al 2007; Hamada, Shino, Horibe et al 2001; Järvelä 2007; Järvelä, Moisala, Sihvonen et al 2008; Kondo, Yasuda, Azuma et al 2008; Muneta, Koga, Morito et al 2006; Siebold, Dehler, Ellert et al 2008; Streich, Friedrich, Gotterbarm et al 2008; Yagi, Kuroda, Nagamune et al 2007; Yasuda, Kondo, Ichiyama et al 2004; Yasuda, Tanabe, Kondo et al 2010; Mae, Shino, Matsumoto et al 2010) have

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achieved conflicting results, with some papers failing to show a difference (Adachi, Ochi, Uchio et al 2004; Hamada, Shino, Horibe et al 2001; Siebold, Dehler, Ellert et al 2008; Streich, Friedrich, Gotterbarm et al 2008; Yagi, Kuroda, Nagamune et al 2007). Recent knowledge of native bundle anatomy (Chapter 2), number of tibial tunnels required (Mae, Shino, Matsumoto et al 2007), tunnel positioning, and graft tensioning (Chapter 5) should improve DB procedures and may lead to different clinical results. At the present time, several DB techniques have been described, including transtibial (Yasuda, Kondo, Ichiyama et al 2004), transportal (Yagi M, Kuroda R, Yoshiya et al 2005), and outside-in approaches (Aglietti, Giron, Cuomo et al 2007; Mae, Shino, Matsumoto et al 2007).

In a Level II clinical trial (Chapter 9), better results in DB ACL reconstruction were achieved with an outside-in technique rather than with a transtibial. This can be explained by a more anatomic femoral tunnel placement achieved by the outside-in technique. The control group consisted of SB transtibial reconstructions. The Level I study presented in this chapter was designed to prospectively compare after a minimum 2-year follow-up outside-in SB and DB reconstructions in patients with chronic ACL injuries treated with the same surgical technique and graft fixation. It was hypothesized that a closer replication of ACL anatomy with a DB outside-in technique is more effective than an outside-in SB reconstruction.

10.2 Materials and Methods

Seventy consecutive patients with a complete, isolated and chronic ACL lesion (injury surgery interval > 6 weeks) were randomized to receive a single (SB) or double bundle (DB) ACL reconstruction with a hamstring graft at Careggi University Hospital in Florence (Italy) where the investigation was performed. Before the investigation was initiated, the sample size was estimated on the basis of the hypothesis that there was no difference in anterior-posterior knee laxity between the treatment groups. A clinically relevant difference between groups was considered to be a 1 mm difference in anterior knee laxity when compared with the contra lateral un-injured side. The standard deviation, as it has been

seen in a previous trial (Giron, Aglietti, Cuomo et al 2005), was set at 1.5 mm. A power calculation was performed with a confidence level of 95% ($\alpha = 0.05$) and a power ($1-\beta$) of 80%. This yielded an estimated sample size of 35 patients per group. The randomization was performed via a computer generated list of random numbers, while the patients were recruited according to the general waiting list by the hospital secretary who was not aware of the study.

All patients fulfilled the following inclusion criteria: 1) closed physes and younger than 40 years old; 2) healthy contra lateral knee; 3) no previous surgeries in the index knee (apart from partial meniscectomy); 4) chondral lesions less than Outerbridge Grade III (Outerbridge, 1961); 5) no patellofemoral symptoms; 6) absence of systemic illnesses; and 7) compliance to enter the 2-year follow-up study. Ethical approval was obtained from the Internal Review Board. All subjects were informed of the study design and gave informed consent, but they were blinded to the type of procedure adopted. The patients became aware of the received procedure after 1 year from surgery, when they underwent a radiographic evaluation.

Patient's demographics, injury history and preoperative assessment

Patients were comparable for age, sex, body weight, height, generalized joint laxity, operated side, preinjury sports activity level, mechanism of injury, time from injury to operation (Tab. 10.1), and preoperative anterior and rotational knee laxity (Tab. 10.2).

	SB # patients	DB # patients
Gender (male/female)	25/10	28/7
Age (years)	28 (range 16-40)	28 (range 16-40)
Side involved (right/left)	19/16	16/19
Body weight (Kg)	73 (range 55-105)	73 (range 55-90)
Height (cm)	175 (range 160-188)	175 (range 160-185)
Type of injury		
Contact	6	9
Non contact	17	19
Motor vehicle accident	10	6
ADL	2	1
Mean (median) injury-surgery interval (months)	24 (12) (range 2-96)	28 (14) (range 2-100)

Table 10.1: Patient demographics

	SB # patients	DB # patients
Lachman test		
+ (3-5 mm)	2	3
++ (6-10 mm)	33	32
+++ (> 10 mm)	-	-
Pivot shift test		
+ (glide)	3	4
++ (clunk)	32	29
+++ (gross)	-	2

Table 10.2: preoperative knee laxity

Generalized joint laxity according to Carter and Wilkinson criteria (1964) was observed in 8 patients in the SB group and in 5 patients in the DB group. Twenty-four patients (69%) in the SB group and 27 patients (77%) in the DB group played pivoting sports before injury. Previous surgery included 4 partial arthroscopic medial meniscectomy in the DB group only. The above differences were not statistically significant.

Surgical technique

All the procedures were performed by one senior experienced surgeon with the use of a tourniquet. Complete ACL tear was confirmed at arthroscopy. The medial meniscus was torn in 10 knees (29%) in both groups. The lateral meniscus was torn in 5 knees (14%) in the SB group and in 3 (9%) in the DB group. Three medial meniscus lesions were sutured in SB Group. A limited partial meniscectomy was performed in all other cases. A stable longitudinal lesion

(< 1 cm) of the medial or lateral meniscus was left untreated in 4 knees (11%) in the SB group and in 5 knees (14%) in the DB group.

Semitendinosus and gracilis tendons were harvested through an oblique approach medial to the tibial tubercle over the pes anserinus by using a smooth tendon stripper (Linvatec, Largo, FL). The tendons were cleaned from soft tissue and the free ends were armed with a N. 1 Vycril absorbable sutures in a criss-crossing Chinese finger-trap pattern. The grafts were pretensioned on the suture board. In both groups, the torn ACL was debrided and the anatomical tibial and femoral footprints of the two bundles, when present, were preserved and marked with a radiofrequency ablator (VAPR, De Puy Mitek, Raynham, MA). No notchplasty was necessary. All graft diameters were measured in 0.5 mm increments, and the tibial and femoral bone tunnels were drilled accordingly.

DB procedure

Two tibial tunnels were drilled. The AMB guidewire was drilled through the Howell 65° Tibial Guide anterior hole as previously described in chapters 8 and 9 (Fig. 10.1).

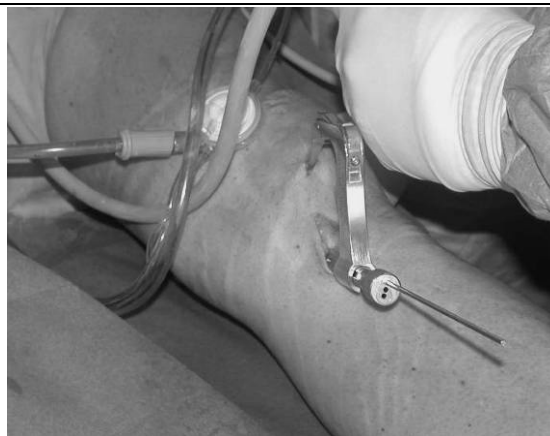


Figure 10.1: AMB guidewire drilled through the Howell guide

The PLB guidewire was drilled with a prototype rod guide (Smith & Nephew, Inc., Andover, MA) which was inserted in the AMB tunnel (Fig. 10.2). The articular exit of the PLB guidewire is at a fixed distance (8 mm) posterior to the centre of the AMB. This prototype guide represents the evolution of a previously validated

guide which was demonstrated to accurately and reproducibly place the tibial guide wire in an anatomic position (chapters 8 and 9). This most recent version of the guide includes a different slot to drill the PLB femoral tunnel. The angulations and directions of the tibial tunnels were preserved.

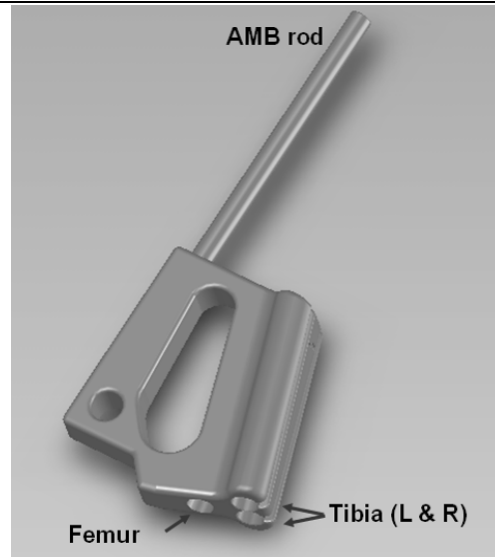


Figure 10.2: PLB tunnel guide. It consists of a size-specific rod inserted in the AMB tunnel and 3 slots for the PLB tunnel, 2 on the tibia (left and right) and one for the femur.

Intra-operative views of the PLB guide are shown in Fig. 10.3.

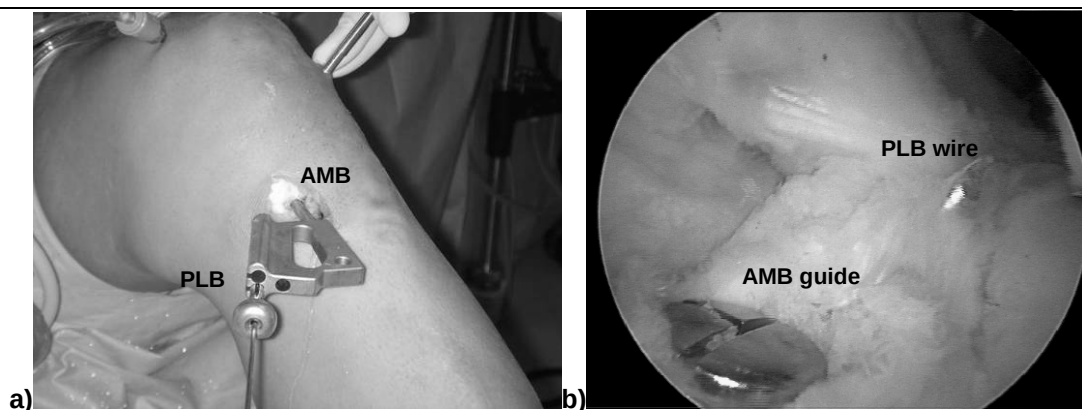


Figure 10.3: a) the PLB guidewire was drilled with a prototype rod guide which is inserted in the AMB tunnel; **b)** the articular exit of the PLB guidewire was 8 mm posterior to the centre of the AMB tunnel and its mediolateral position could be adjusted relying on an aiming sulcus on the tip of the rod.

The two femoral tunnels were drilled outside-in keeping the knee at 90° of flexion. The arthroscope was inserted into the joint from the anteromedial portal, looking

at the lateral wall of the notch. The view from the anteromedial portal is particularly useful for adjustment of the deep-shallow position of the tunnels (Chapter 2). The AMB guidewire was inserted with a front-entry outside-in guide (Shino Guide, Smith & Nephew, Inc., Andover, MA) as deep as possible on the lateral wall below the over the top position so to have the entire tunnel exit on the lateral wall and not on the roof (Fig. 10.4).

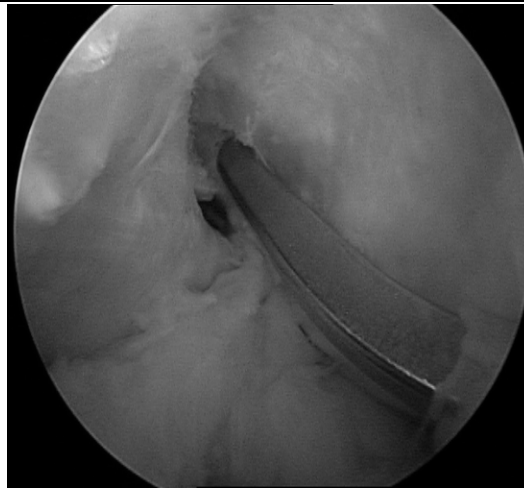


Figure 10.4: Arthroscopic view from anteromedial portal showing the intra-articular arm of the Shino guide and the point we aimed on the lateral wall of the notch to drill the AMB wire (knee at 90° of flexion).

The PLB wire was drilled 9 mm apart and shallow about 5 mm from the cartilage border (Chapter 2), using the same prototype rod guide described for the tibial PLB tunnel but through a different hole (Fig. 10.5). With the knee at 90° of flexion the two tunnels in the femur are almost in line and parallel to the tibia.

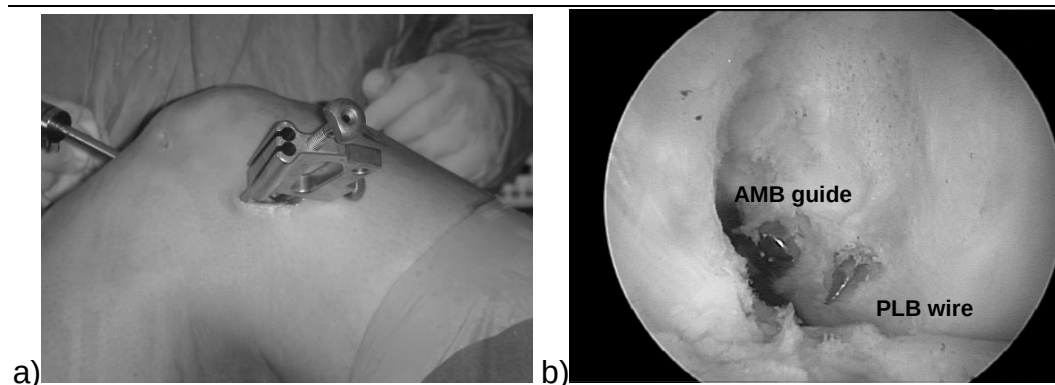


Figure 10.5: a) the PLB guide inserted in the AMB femoral tunnel ;b) PLB wire drilled 9 mm apart from AMB and shallow about 5 mm from the cartilage border.

A bony bridge between the tunnels was always present (Fig. 10.6).

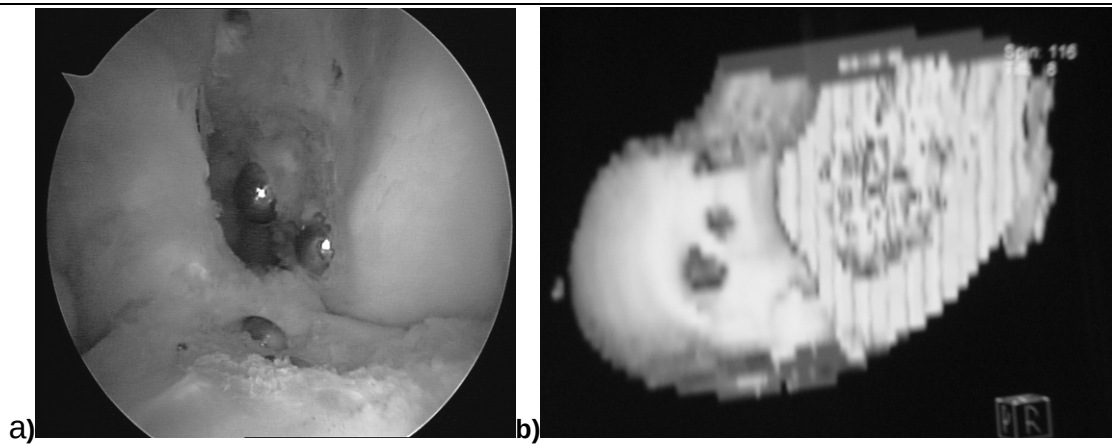


Figure 10.6: a) arthroscopic view from anteromedial portal showing the position of the two exit holes of the two femoral tunnels into the wall of the notch. A bony bridge between the tunnels was always present; b) 3D CT scan sagittal view showing the position of the intra-articular exits of the femoral tunnels on the wall of the notch.

A single semitendinosus and gracilis tendon graft was looped around the bony bridge between the two tibial tunnel exits and stitched to periosteum. The tendon free ends were passed into the joint and exited the lateral femoral cortex. PLB and AMB grafts were fixed at 20° and 40° of flexion, respectively, with two 6 mm outside-in titanium Rounded Cannulated Interference (RCI) screws (Smith & Nephew, Inc., Andover, MA), under a manual tension per bundle of approximately 20 N. An additional staple secured both grafts to the femoral cortex (Fig. 10.7).



Figure 10.7: x-rays after DB reconstruction

SB procedure

The tibial guidewire was drilled with the Howell 65° Tibial Guide (Arthrotek, Warsaw, IN) as previously described (Chapter 7). On the femur the attachments of the two bundles were marked as performed in the DB technique and an “anatomic” (not isometric) SB tunnel was drilled outside-in on the lateral wall of the notch, right in the middle of the AMB and PLB attachments, using the same Shino guide (Fig. 10.8).

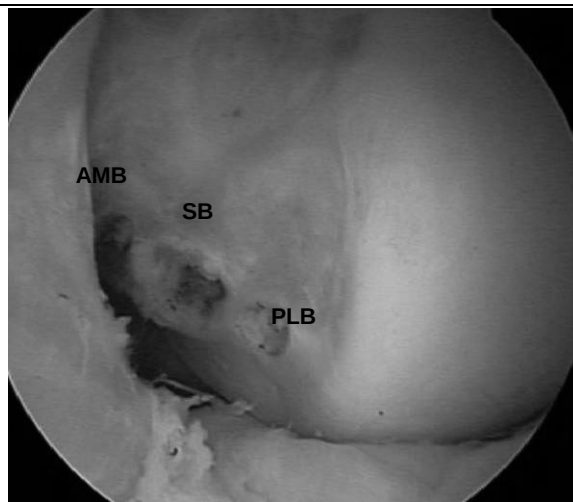


Figure 10.8: in the SB technique the femoral guide wire was drilled aiming a position in the middle of the AMB and PLB attachments.

A pretensioned doubled semitendinosus and gracilis graft was mounted on the working station with the PAG tibial device (Citieffe, Bologna, Italy) and passed into the joint. The PAG is a suspension device and consists of a cortical low profile titanium button articulating with an eyelet of variable length (10 or 20 mm) where the tendons are looped around (Fig. 10.9). Femoral fixation was achieved with a 7 or 8 mm titanium RCI screw at 20° of flexion after cycling under a manual tension of approximately 40 N. An additional staple on the lateral femoral cortex was employed to improve fixation (Fig. 10.9).

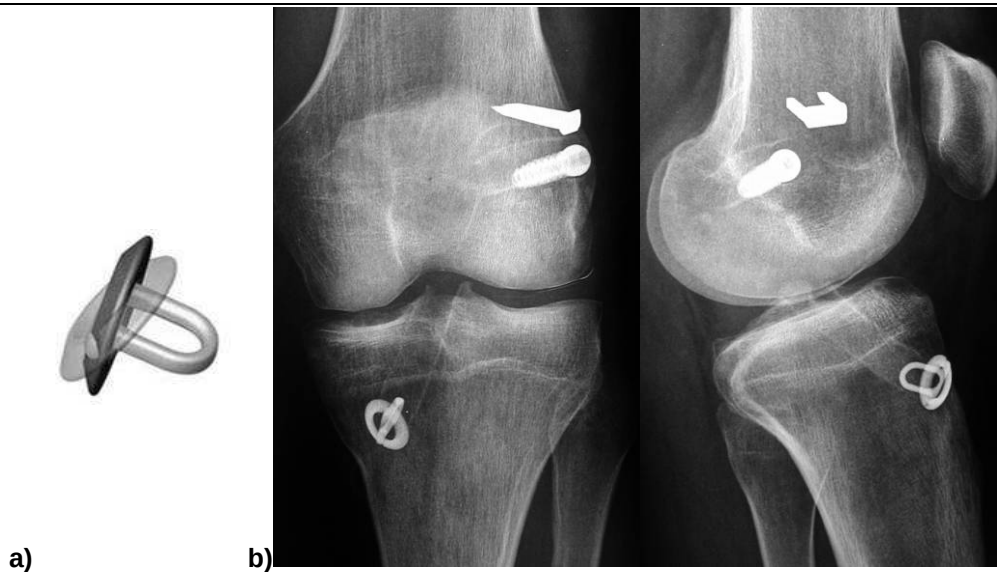


Figure 10.9: a) PAG suspension device; b) postoperative radiographic A-P and L-L views after ACL reconstruction using SB technique (left knee). A metallic suspension device (PAG) which relied on the tibial cortex was employed to fix the graft distally.

A previously described brace-free rehabilitation protocol (Aglietti, Giron, Buzzi et al 2004) was adopted in both groups and initiated after one week of postoperative isometric strengthening and flexion restriction. Full range of motion and closed chain strengthening exercises were initiated after 4 and 6 weeks, respectively. Running was allowed after 3 months and return to sports-specific training after 4 to 5 months.

Follow-up examinations

All the patients were evaluated before surgery: every 2 weeks up to the second postoperative month; monthly up to 4 months after surgery; and then at one and two years thereafter by an independent and blinded observer. Both knees of the patient were covered with a stockinette to prevent any information about operated side and the incisions.

Subjective examination

All the patients were evaluated using the Visual Analogue Scale (VAS) (Flandry, Hunt, Terry et al 1991), the Knee injury and Osteoarthritis Outcome Score

(KOOS) (Roos, Roos, Lohmander et al 1998) and the new International Knee Documentation Committee (IKDC) evaluation form (Irrgang, Anderson, Boland et al 2001). To assess the VAS, the patient was asked to answer the following question: "How would you rate the function of your knee?" marking the score on a line divided in ten points with 0 labelled as "very poor" and ten labelled as "excellent". KOOS consists of 5 subscales; Pain, other Symptoms, Function in daily living (ADL), Function in sport and recreation (Sport/Rec) and knee related Quality of life QOL. Standardized answer options are given (5 Likert boxes) and each question gets a score from 0 to 4. A normalized score (100 indicating no symptoms and 0 indicating extreme symptoms) is calculated for each subscale. The IKDC subjective form consists of 10 questions on symptoms, sports activities and function; an overall 0 to 100 (no limitation) score is then calculated.

Objective examination

The objective examination was performed according to the IKDC objective form (Irrgang, Anderson, Boland et al 2001) which includes three categories: effusion, passive motion deficit and ligament examination (Tab. 10.3).

	A Normal	B Nearly Normal	C Abnormal	D Severely Abnormal
1. Effusion	☐ None	☐ Mild	☐ Moderate	☐ Severe
2. Passive Motion Deficit ΔLack of extension ΔLack of flexion	☐ <3° ☐ 0 to 5°	☐ 3 to 5° ☐ 6 to 15°	☐ 6 to 10° ☐ 16 to 25°	☐ >10° ☐ >25°
3. Ligament Examination (manual, instrumented) ΔLachman (25° flex) (134N) ΔPivot Shift	☐ -1 to 2mm ☐ equal	☐ 3 to 5mm(1+) ☐ <-1 to -3 ☐ +glide	☐ 6 to 10mm(2+) ☐ <-3 stiff ☐ ++(clunk)	☐ >10mm(3+) ☐ +++(gross)

Table 10.3: objective IKDC examination

Range of motion was measured in relationship to the opposite normal knee using a long arm goniometer. Extension deficit was determined with the subject lying in the prone position with the leg hanging out of the bed, so hyperextension was allowed. Side to side difference was evaluated both with a long arm goniometer and as heel height difference with the contralateral limb.

Side to side difference in anterior tibial translation was assessed with the knee flexed 30° using the KT-1000 arthrometer (Medmetric, San Diego, California) at 134-N and manual maximum force (Daniel, Malcom, Losse et al 1985). The pivot shift test was performed with the patients supine as described by Galway and MacIntosh (1980) and graded according to the IKDC form as absent, glide, clunk and gross when compared to the contralateral knee.

The final IKDC objective score is determined by the worst group grade.

Statistical analyses

All statistical analyses were conducted on Stat Win II software (StatSoft, Tulsa, OK, USA). The Student's t test was used to compare differences between groups and used the Chi-square test and Fisher's exact test for categorical variables. In all tests, an alpha level of 0.05 was considered significant.

In vivo kinematics measurements

At the 1-year follow-up examination the first 15 consecutive patients in each group underwent in vivo measurement of the anterior translation and internal rotation limit with flexion. Two electromagnetic tracking sensors (Nest of Birds – Ascension Technology, Burlington, USA) were mounted on one leg and one thigh splint which were rigidly fixed to femur and tibia, respectively. The femoral splint consisted of a metaphyseal clamp fixed to the epicondyles and articulating to a bar which was fixed with a velcro strap to the mid-portion of thigh (Fig. 10.10). This design minimizes splint-femur motion and has been validated to be accurate in measuring translations and rotations (Amis, Cuomo, Siva Rama et al 2008).

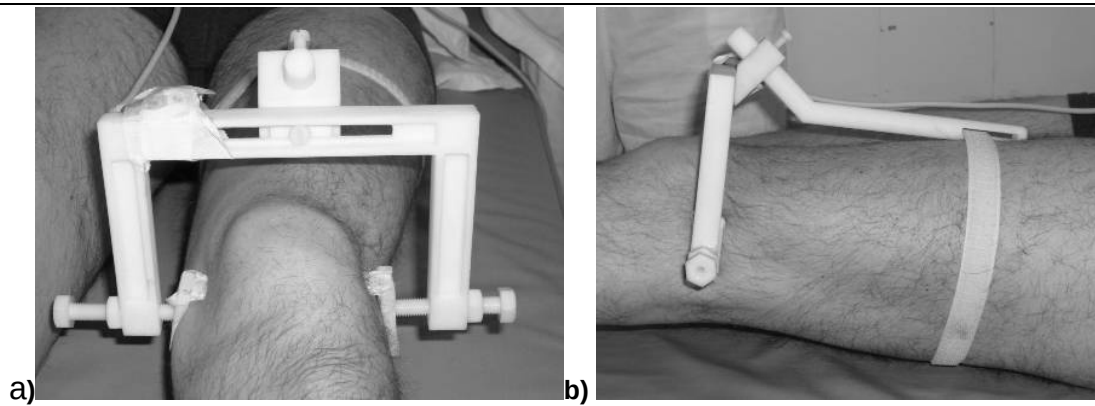


Figure 10.10: frontal (a) and side (b) view of the femoral splint.

On the leg, the sensor was fixed with an elastic bandage to the medial aspect where the tibia is flat and covered only by the skin (Fig. 10.11). This setup was validated to minimise skin-sensor movements (Amis, Cuomo, Siva Rama et al 2008).



Figure 10.11: sensor (arrow) covered by an elastic bandage on the medial aspect of the leg

A third sensor was instrumented with a stylus and was used to digitise the medial and lateral malleoli and the medial and lateral aspect of the femoral clamp (Fig. 10.12).



Figure 10.12: digitising sensor

The mechanical axis of the lower limb could then be calculated based on the above digitised points and on centre of the hip joint which was determined with circular movements of the hip with the knee in extension.

6 DOF kinematic data through an 80° flexion-extension cycle were recorded and interpolated at 1 degree flexion increments in the following conditions: 90N posterior drawer, 90N anterior drawer, 5Nm internal rotation torque. These loading conditions resemble the ones applied in the laboratory (Chapters 3,4,5). To apply the 90N posterior drawer a 50N sand bag was held on the anterior aspect of the leg, assuming that the remaining 40N are provided by the weight of the leg itself. The 90N anterior drawer was given through a 90N constant spring force which provided the same force from a 15cm length onward (Fig. 10.13).



Figure 10.13: 90N anterior drawer applied through a constant force spring

The tibial internal rotation torque (5Nm) was provided with a pair of constant force springs to provide a couple and attached to a rigid boot (Fig. 10.14)

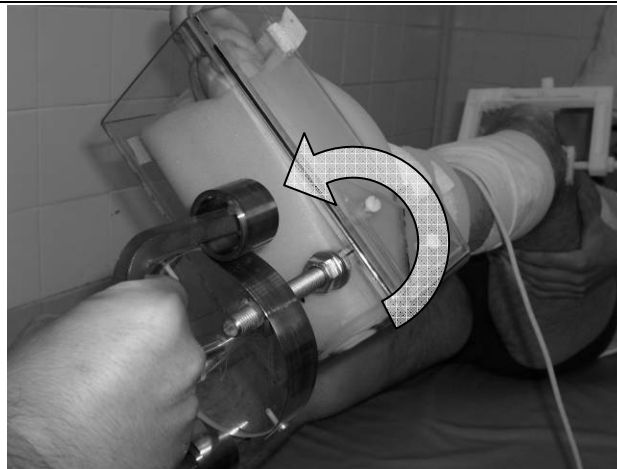


Figure 10.14: 5Nm internal torque applied to the tibia

Anterior drawer and internal rotation interpolated data were normalised to the posterior drawer condition. This explains the apparently larger anterior knee laxity (Fig 10.15) when compared to cadaver laxity which was normalised to the neutral condition (chapters 3,4,5). Measurements were obtained from the reconstructed and the uninjured knee. 95% confidence interval anterior and internal rotation laxity bands were then plotted.

10.3 Results

Clinical results

No intraoperative or postoperative complications were recorded.

Three non-traumatic failures for instability were recorded at one-year follow-up, 1 in the DB group and 2 in the SB group. A traumatic rupture was recorded at two-year follow-up in the SB group. None of the patients underwent a revision ACL procedure. Two other patients in DB group underwent surgery during the follow-up period. In one case, at one year from ACL surgery, the hardware was removed due to pain and swelling in the distal part of the ileo-tibial band during sports activities. Another patient with a longitudinal and stable lesion of the posterior horn of the medial meniscus at the time of ACL reconstruction suffered a new meniscal lesion while playing volley at 18 months from the ACL reconstruction. A partial medial meniscectomy and a second look showing a good and competent ACL was performed.

Subjective results

Mean VAS, KOOS and subjective IKDC scores significantly increased with time and improved compared to the preoperative scores. No differences were found between the two groups in IKDC subjective score and KOOS. After two years the VAS score was significantly higher in the DB group ($p<.04$) (Tab. 10.4)

	4-months follow-up		1-year follow-up		2-year follow-up	
	SB	DB	SB	DB	SB	DB
VAS (0-10;10 normal)	6.3±2	7.5±1.8	6.9±2	7.9±1.8	7.6±2.2	8.6±2.2
	P<0.05		P<0.04		P<0.04	
KOOS						
Pain	89±10	90±11	90±6	92±8	93±7	93±8
Symptoms	84±13	86±11	86±7	86±11	90±8	90±9
Activities of daily living	95±6	94±9	94±8	96±7	95±7	98±2
Sports activities	75±21	74±22	77±12	81±18	88±12	86±16
Quality of life	67±19	67±23	71±18	71±23	80±18	77±17
	n.s.		n.s.		n.s.	
Subjective IKDC score	72±15	74±16	74±12	78±15	78±13	83±15
	n.s.		n.s.		n.s.	

Table 10.4: subjective results

Objective results

All the patients recovered full range of motion within 4 months from surgery. In SB and DB group knee extension was $-2.4 \pm 1.7^\circ$ and $-2.1 \pm 1.4^\circ$, respectively, and maximum flexion was $133.1 \pm 5.9^\circ$ and $133.3 \pm 3.4^\circ$, respectively. As to knee extension, the heel height side to side difference in prone position with the leg hanging from the table was within 1 cm in all cases.

At the last follow-up, a 1+ Lachman test with a firm end point was recorded in all the patients but 4 (3 in SB group and 1 in DB group). A pivot shift glide (1+) was recorded in 9 knees (26%) in the SB group and in 5 knees (14%) in the DB group.

Three patients (9%) in SB group and one patient (3%) in DB group had a pivot-shift clunk (2+). The differences between the two groups were not statistically significant.

The average KT-1000 side to side anterior tibial translation showed a significant decrease compared to the preoperatively measurements at each follow-up in both groups ($p<.001$). At 1- and 2-year follow-up the average decrease in instrumented knee laxity was statistically significant in DB group compared to the SB group ($p<.04$) (Tab. 10.5).

	SB	DB	Significance
Average KT-1000 anterior SSD* at 134N			
Preoperatively	7.0±1.5	6.8±1.4	n.s.
4-month follow-up	1.5 ±1.0	1.3±1.3	n.s.
1-year follow-up	2.1±1.5	1.2±1.4	$p<.04$
2-year follow-up	2.3±1.4	1.3±1.3	$p<.04$
Significance preop vs postop	$p<.001$	$p<.001$	

Table 10.5: KT-1000 anterior side to side difference* (SSD) measurement in anterior tibial translation preoperatively and at follow-up

At 2-year follow-up the final IKDC score showed significantly more normal results in DB group ($p=.03$) and the overall objective IKDC categories were: normal in 28 (80%) DB and in 20 (57%) SB patients ($p=.03$); nearly normal in 6 (17%) DB and 12 (35%) SB patients; abnormal in 1 (3%) DB and 3 (9%) SB patient, respectively (Tab 10.6).

IKDC final objective score	SB	DB
Normal	20	28*
Nearly normal	12	6
Abnormal	3	1

Table 10.6 IKDC final objective score. * $p=0.03$

No correlations were found between clinical outcomes and gender, meniscectomy, generalized laxity and anthropometric measurements (height and weight), although the statistical power of the study was not sufficient to test for differences in these variables..

Before ACL injury, 71% (25 out of 35) of the patients in the SB group and 80% (28 out of 35) of patients in the DB group were involved in IKDC level I or II sports activities. At 2-year follow-up, 17 patients (49%) in the SB group and 23 (66%) in the DB group were active in Level I or Level II sports activities. When comparing the preoperative and postoperative IKDC level in every single patients it was found that nineteen patients (54%) in SB group and 24 patients (69%) in DB group were able to recover the same pre-injury sports activity level.

Instrumented laxity results

SB bundle reconstruction anterior translation limit was close to the uninjured side towards extension and it shifted anteriorly from 15° of flexion onward. DB reconstruction 90N anterior translation limit closely replicated uninjured knees laxity (Fig. 10.15)

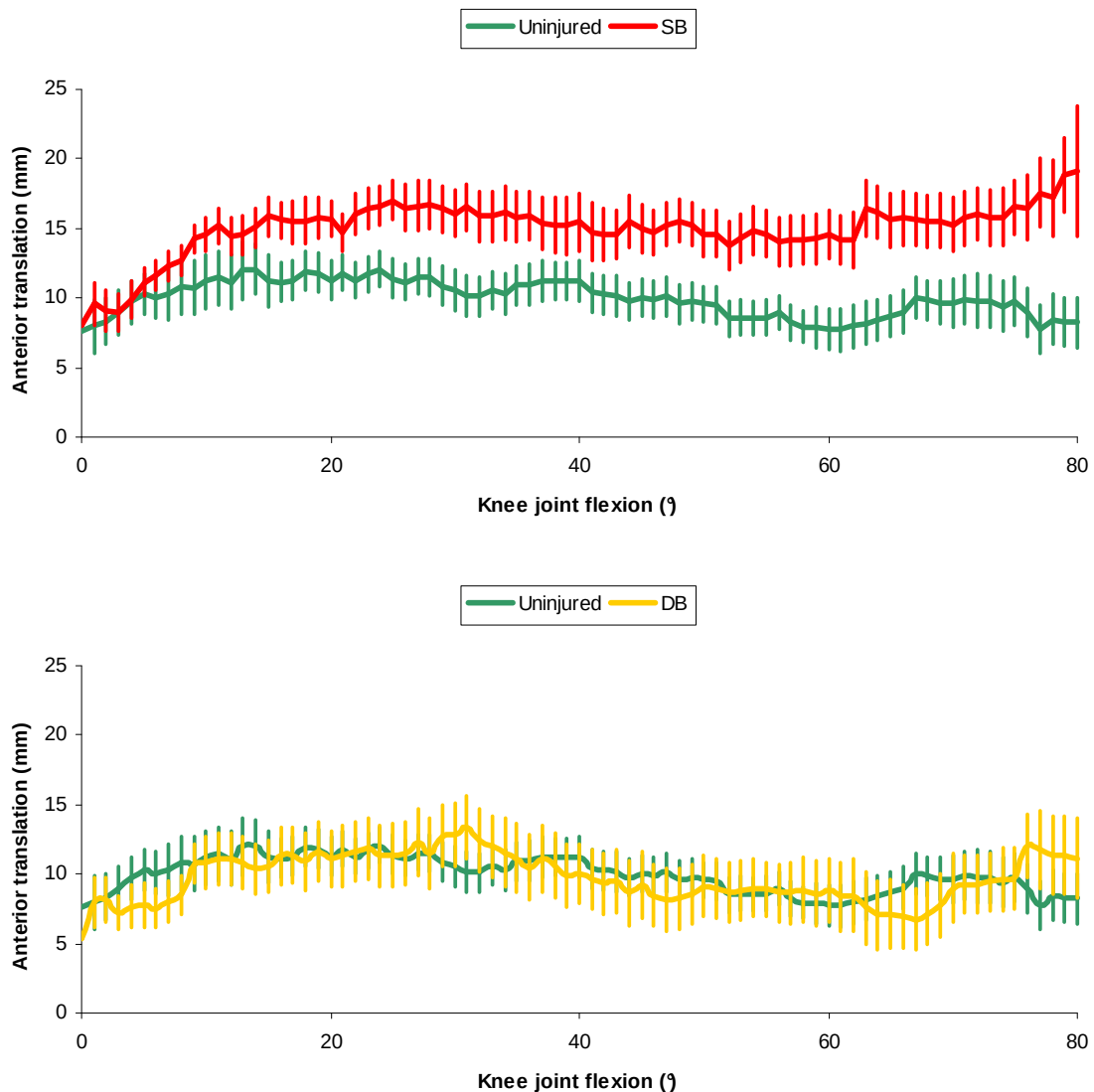


Fig. 10.15: 90N anterior translation limit 95% confidence interval after SB (upper plot) and DB (lower plot). Green lines represent uninjured knees CI. All data are normalised to 90N posterior drawer condition.

The limit of internal rotation was slightly affected by any of the ACL procedures, with a tendency to a mild decrease in internal rotation limit, particularly after SB reconstruction (Fig. 10.16)

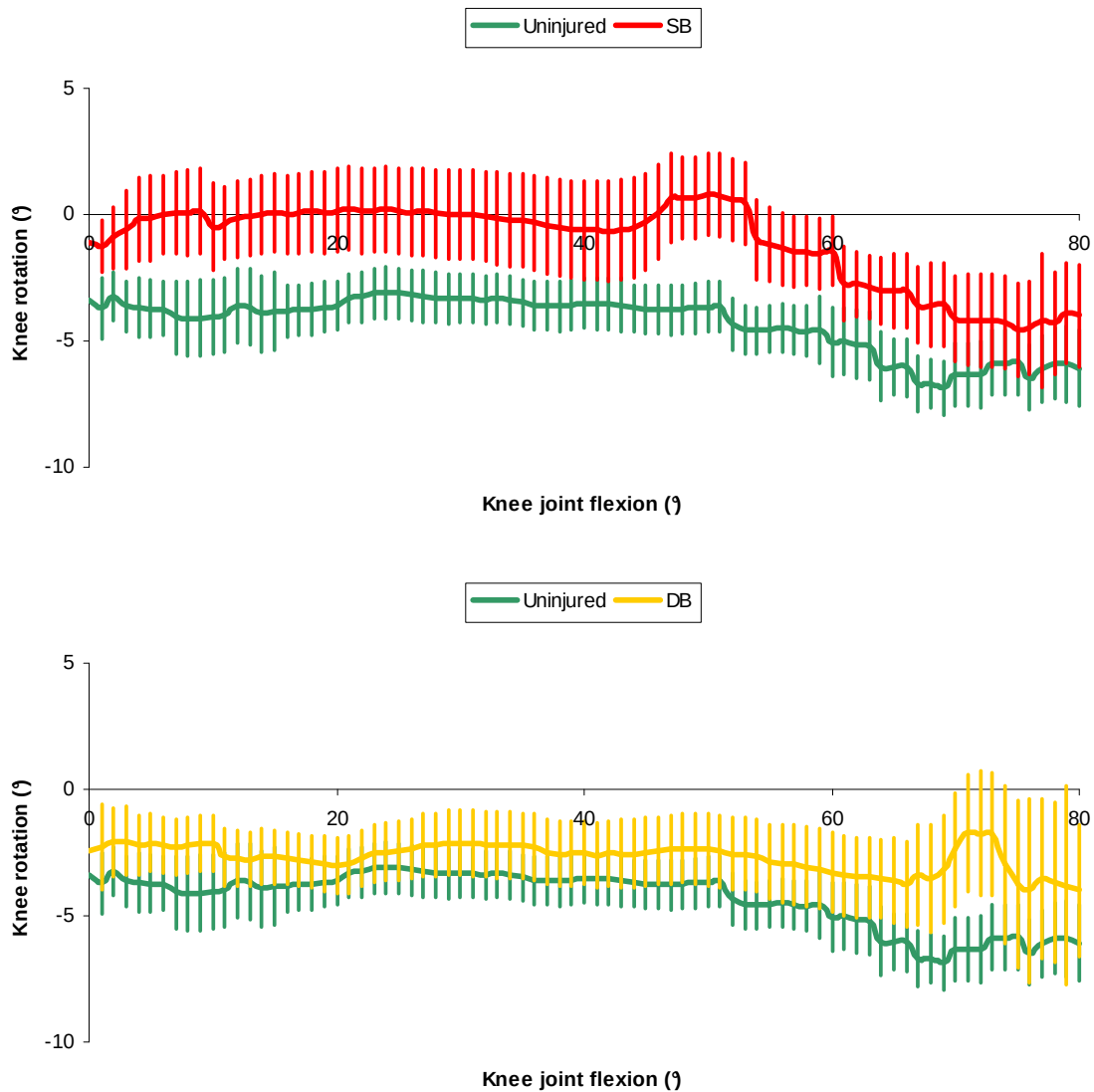


Fig. 10.16: 5Nm internal rotation torque limit 95% confidence interval after SB (upper plot) and DB (lower plot). Green lines represent uninjured knees CI. All data are normalised to 90N posterior drawer condition. Positive values mean external rotation.

10.4 Discussion

The main finding of this investigation is that, after a 2-year minimum follow-up, out-in DB ACL reconstruction showed better VAS, final IKDC objective score, and improved anterior knee stability compared to SB reconstruction. A trend towards less pivot shift and more sports activities recovery was also observed. Furthermore a methodology to measure in vivo knee laxity, introducing into clinics

the laboratory method (Chapters 3,4,5), was presented and used on a preliminary series here. DB patients had improved anterior knee stability; both reconstructions (SB and DB) had small effects on pure rotations as demonstrated in previous chapters (4,5).

DB ACL reconstruction was introduced to replicate native ACL anatomy which consists of two main functional bundles, the AMB, taut through full range of knee motion and the PLB, taut mainly towards extension (Radford, Amis 1990). The different behaviour of the two bundles should affect knee kinematics and it has been hypothesized (Gabriel, Wong, Woo et al 2004; Zantop, Herbolt, Raschke et al 2007) that the AMB, which is closer to the line of knee axial rotation, controls mainly anterior laxity while the PLB, which is more divergent to the axis, should better control rotation. The latter should also be involved in controlling the pivot shift phenomenon, which is a combination of abnormal rotation and translation.

In vitro laboratory studies have confirmed the superiority of the DB reconstruction in controlling anterior tibial translation and internal rotation (Chapter 5). Conversely, in vivo comparative studies have led to different and sometimes conflicting results (Adachi, Ochi, Uchio et al 2004; Aglietti, Giron, Cuomo et al 2007; Hamada, Shino, Horibe et al 2001; Jarvela 2007; Järvelä, Moisala, Sihvonen et al 2008; Kondo, Yasuda, Azuma et al 2008; Muneta, Koga, Morito et al 2006; Siebold, Dehler, Ellert et al 2008; Streich, Friedrich, Gotterbarm et al 2008; Yagi, Kuroda, Nagamune et al 2007; Yasuda, Kondo, Ichiyama et al 2004). While laboratory experiments place the graft exactly at the site of native bundle attachments, in vivo experiences suffer the drawbacks of the subjectivity of tunnel positioning in the lack of definitive landmarks. Furthermore, different approaches (i.e. transtibial, transportal, outside-in) lead to different tunnel positions (Chapter 9; Giron, Buzzi, Aglietti 1999).

Adachi, Ochi, Uchio et al (2004) found no differences between SB and DB reconstruction with a preliminary technique, consisting of one tibial and two transtibial femoral tunnels. Järvelä(2007) after one year reported superior stability results both translational and rotational in DB group with a transportal technique. After two years his results were confirmed (Järvelä, Moisala, Sihvonen et al 2008). In those studies he also reported a higher incidence of failures with the SB

technique. Streich, Friedrich, Gotterbarm et al (2008) and Siebold, Dehler, Ellert (2008) using a transtibial technique both for SB and DB reconstruction found no advantages in using a DB technique. With the same approach Kondo, Yasuda, Azuma et al (2008), in a comparative but not randomized study, evaluated 328 consecutive patients and observed improved anterior stability and less pivot shift in DB than in SB reconstruction.

In Chapter 9, which was a comparative Level-II study, better anterior and rotational stability results were observed only when comparing DB out-in to SB transtibial. There were no differences between DB transtibial and SB. On the basis of these conflicting in vivo results it can be hypothesized that tunnel placement plays a major role in DB reconstruction outcome.

The transtibial technique has the advantage of achieving a reproducible tunnel positioning but this is limited by the position and angulation of the tibial tunnels. Moreover cadaveric studies showed that the transtibial approach is not accurate both in SB (Giron, Buzzi, Aglietti 1999; Arnold, Kooloos, van Kampen 2001) and in DB ACL reconstruction (Chapter 8). The transportal technique is less constrained but anatomy knowledge is required to place the tunnels in the proper position. The double incision outside-in approach is today not very popular, mainly due to the lateral accessory incision that is required. Besides that, the available jigs easily allow the most posterior and proximal part of the lateral notch to be reached which is where the ACL attachment lies.

In the recent years, under the enthusiasm for the DB technique, the ACL attachments anatomy particularly on the femoral side has been revisited (Chapter 2). On the femur the ACL fibers attach exclusively on the wall and not on the roof of the notch. From an arthroscopic point of view it is useful to remember that the whole femoral ACL attachment lies along the posterior articular cartilage border and is vertical with the knee in extension and assumes a horizontal direction with the knee at 100° of flexion (Siebold, Ellert, Metz et al 2008). As two bundles attach at 90° of flexion, the AMB is deep and high just below the over-the-top. The PLB attachment is shallow 5 mm from the cartilage contour (Yasuda, Kondo, Ichiyama et al 2005).

With an outside-in approach the surgeon is free to select the desired position on the wall according to his experience and to the data available from the literature. As a consequence this study was designed to compare a DB technique to an anatomic SB according to the recently revised anatomic landmarks (Chapter 2). However, in the present study no CT or MRI scan was performed after surgery in order to evaluate tunnel position even if in Chapter 9 an improved MRI tunnel positioning was observed after outside-in drilling.

In this study the same surgical technique was employed in both groups including graft type, out-in technique, and graft fixation. The latter relied on cortical bone fixation on the tibia and interference screw plus a staple on the femur. This unique graft fixation technique ensures that the whole length of the tunnel is filled with the graft and a very strong cortical fixation on the tibial side. Furthermore in this DB technique the AMB and PLB grafts have the same diameter. Finally the SB tunnel was placed right in the middle of the two bundle tunnels, in the femur and tibia.

After two years the DB group showed better anterior stability results. No statistically significant difference in term of residual pivot shift incidence, but only a trend in favour of DB, was observed; this is different to the study in Chapter 9. This could be ascribed to: 1) a better performance of the “anatomic” SB out-in reconstruction; 2) the subjectivity of pivot shift testing and grading; 3) the relatively small number of patients. With the current data a posthoc power analysis was performed to estimate the sample size required to analyze the pivot shift. As a result 72 patients per group would be necessary. On the other hand, with an objective arthrometric measurement significant differences between the two groups were observed in term of anterior tibial translation.

A criticism could be made to the emphasis given to KT stability results. KT inaccuracy has been reported by some researchers (Graham, Johnson, Dent 1991; Wiertsema, van Hooff, Migchelsen 2008). On the other hand when side to side differences are examined the accuracy of the system becomes comparable to RSA and ultrasound measurements (Pugh, Mascarenhas, Arneja 2009). Furthermore despite in this study an intraexaminer reliability study was not

performed, other researchers have documented intraexaminer reliability greater than 0.8 (Pugh, Mascarenhas, Arneja 2009).

No definitive conclusions can be drawn about the pivot shift. Sample size was calculated on a KT-1000 anterior tibial translation difference greater than 1 mm and this allowed significant differences to be found. Furthermore pivot shift assessment still remains subjective and an instrumented measurement is needed. Nevertheless a trend towards pivot-shift reduction was evident and encouraging.

Finally in this study a way to export in a clinic basic science methodology (Chapter 3) was introduced. None of the patients complained of any discomfort during the non invasive procedure. Though being a preliminary experience, the kinematics results are in line with the arthrometric KT results from patients in the same series and with cadaver laboratory tests where the same methodology and the same loads were employed (Chapter 5). After mastering the protocol, in vivo tests could be completed in 15 minutes per patient. Therefore, this methodology can now be considered for routine research purposes in consideration of the relatively low costs and easy use.

In conclusion, after two years the clinical results are in favour of the DB reconstruction as demonstrated by the better VAS and final IKDC scores and lower KT-1000 side to side difference in anterior tibial translation. A trend in favour to DB group in pivot shift incidence and sports activity recovery was recorded, but did not reach a statistical significance.

Chapter 11 – Thesis Discussion and Future Directions

The purpose of this thesis was to verify whether in patients with a traumatic ACL insufficiency it is necessary to closely replicate anatomy of the native ACL to improve the outcome of the reconstruction or to keep on using standard techniques. This was performed at different levels with a multidisciplinary approach (Fig. 11.1): first, in the anatomy laboratory, the gross anatomy of the ACL was revisited with regards to its double bundle structure (Chapter 2) and surgical strategies to replicate it were tested (chapters 7 and 8). In the meantime, in the biomechanics laboratory a knee kinematic testing apparatus was setup (Chapter 3) and intact knee kinematics measured and revisited with regards to ACL and its bundles function (chapters 3 and 4). Then, in the same setting, DB ACL reconstruction kinematic performance was tested (Chapter 5). Finally, the biomechanics and anatomy laboratory acquisitions were exported into a clinical setup and DB reconstruction clinical and instrumented outcomes were compared to conventional SB reconstruction (chapters 9 and 10).

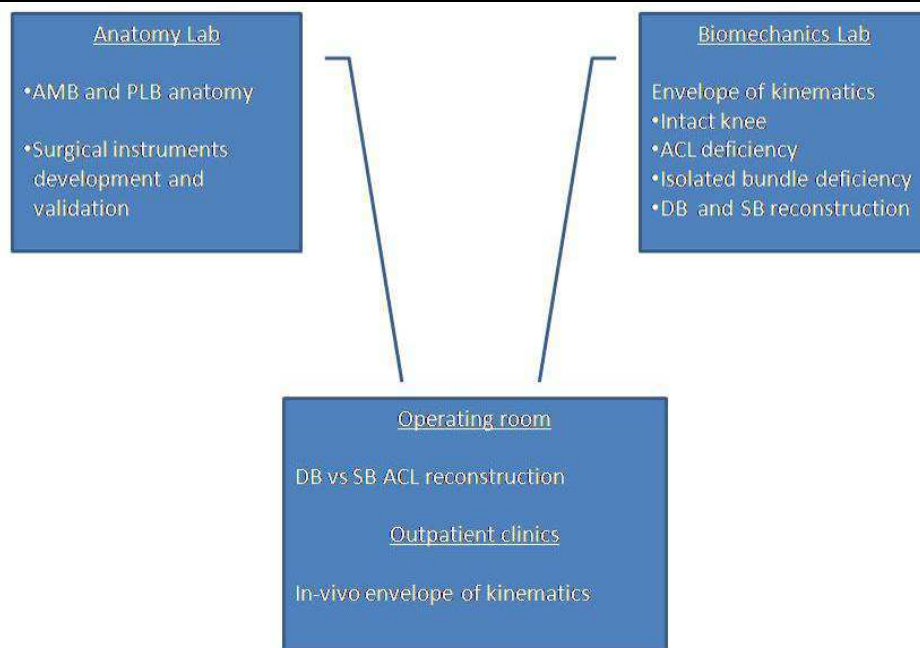


Figure 11.1: thesis multi-level structure

The close replication of the native anatomy of a deficient structure to restore its function is an intuitive concept. Sometimes, however, the native structure of an organ or a segment is extremely complicated so that the simple imitation of its shape is not sufficient to replace its function and functional non-anatomic alternatives may be more effective (Fig. 11.2).



Figure 11.2: Paralympic runner Oscar Pistorius wearing his carbon fibre artificial limbs that provide enhanced performance for a specific task only (running)

As to knee surgery, prior to understanding the complex anatomy and biomechanics of the ACL, early interventions to compensate its anterior translation restrain function included extra-articular procedures, like fascia lata advancement (Lemaire, 1975 | Fig. 11.3) with a strip of fascia lata which was fixed on the tibia anteriorly to its anatomic insertion, to resist anterior shear forces.

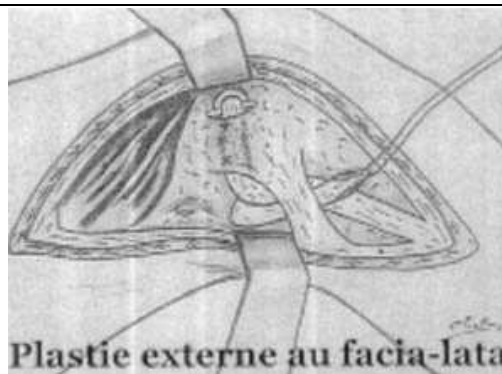


Figure 11.3: Lemaire fascia lata advancement (Lemaire, 1975))

Anatomic DB ACL reconstruction is an old concept. In the 1980s Zariczyj (1987) was one of the first surgeons to perform an “anatomic” ACL reconstruction. In his technique he “imitated” the native shape of the ACL. At a first glance the ACL has a triangular shape with a wider tibial attachment and a narrower femoral insertion (Fig. 11.4).

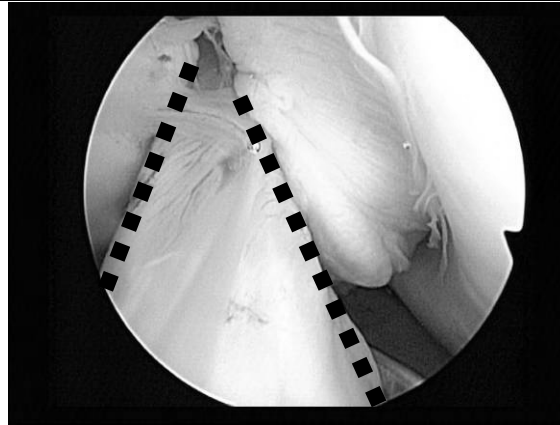


Figure 11.4: knee arthroscopy showing the ACL covered by its synovial sheath with an apparently broader tibial attachment and a quasi-triangular shape

To imitate and replicate this shape Zariczyj (1987) employed a doubled semitendinosus graft passed through two tibial tunnels and one femoral tunnel. Nowadays such a configuration would be considered heretical on the basis of subsequently acquired anatomic and biomechanical information (chapters 2,3,4,5). As a matter of fact a 2 tibial - 1 femoral tunnel reconstruction in the literature has been tested in the laboratory only by Edwards, Guanche, Petrie et al (1999) who demonstrated its inferiority to other modern techniques.

This thesis started from the understanding of the complex native ACL anatomy which consists of two main bundles, the AMB and PLB, which are parallel in extension and when the knee joint flexes they seem to be twisted one round the other because of their different tensions, with the AMB still taut in flexion and the PLB relaxed (chapters 2, 4, 5).

The anatomic work in this thesis mainly looked at locating the attachments of the two bundles on femur and tibia in order to replicate their position at surgery. Current literature has been found to be conflicting with no definitive anatomic landmarks so far (Chapter 2). Therefore in Chapter 2 an anatomic study has been

presented and its results have been employed to validate the surgical instruments that have been presented in chapters 7 and 8. There was the initial ambition to invent an accurate, reproducible and “automatic” surgeon-independent technique thus avoiding the need to identify the bundle attachments at arthroscopy. The proposed surgical transtibial technique resulted in an extremely precise and accurate location on the tibia (Fig. 8.10) while it was less accurate on the femur (Fig. 8.12). When tested in living patients in a Level-II comparative study (Chapter 9), the above mentioned technique resulted to be inferior to the double-incision technique where the femoral tunnel entries were chosen by an experienced surgeon. As a consequence the latest evolution of the technique (Chapter 10) relies on “automatic” instruments (Chapter 8 and 9) for the tibia, without the need to identify bundles’ attachments while on the femur the tunnels are drilled outside-in with a point and shot guide relying on surgeon’s knowledge and experience. A simple way to by-pass the complicated coordinates proposed in the literature (Chapter 2) is to drill the two femoral tunnels on the wall of the notch assuming that the AMB is as deep as possible, below the over the top position, and the PLB is just shallow to it with the knee at 90° of flexion. With the knee in extension the whole attachment area becomes vertical (Fig 11.5).

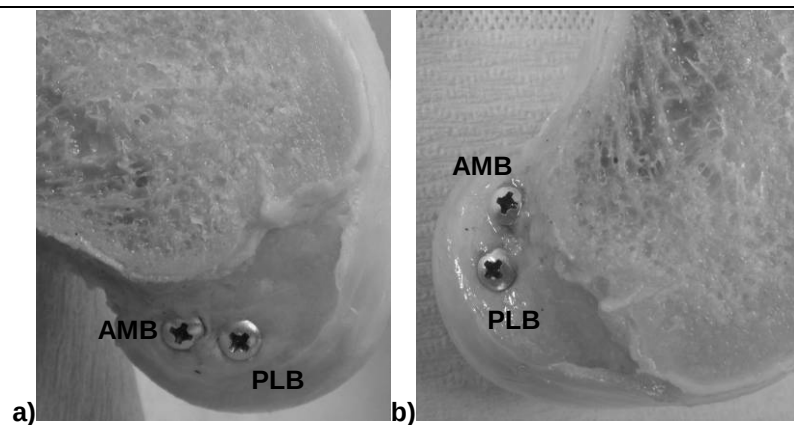


Figure 11.5: AMB and PLB attachment sites (Chapter 2): (a) they are horizontal with the knee at 90° of flexion (arthroscopic view) and vertical (b) with the knee in extension (anatomic description)

The close replication of ACL bundle anatomy at surgery is not enough and must take into account the biomechanics of the native ACL and its bundles. In Chapter 3 a testing apparatus was setup to investigate the role of the ACL in

controlling (Fig. 3.2) the limits of knee motion and it was found that it has a major control of tibia anterior translation (Fig. 3.9) and a minimal, though significant, effect on tibial internal rotation (Fig. 3.13). A laboratory study has been performed and presented in Chapter 4 to investigate the relative contribution of the AMB and PLB to ACL function and it emerged that they are a primary and a secondary restraint to anterior tibial translation, respectively (Figs. 4.4 and 4.5). Both bundles are necessary to control internal rotation (Figs. 4.6 and 4.7). Furthermore it was demonstrated that while the PLB is taut mainly towards extension, the AMB is tensed through the range of flexion-extension (Fig. 4.8). On the basis of this latter study it was hypothesized that a differential fixation strategy (AMB in flexion and PLB in extension) would be necessary to replicate the native bundle tension patterns in DB anatomic ACL reconstruction. This was found not to be optimal as in the experimental work presented in Chapter 5 it was demonstrated that simultaneous fixation of the two bundles graft better restores intact knee anterior translation and internal rotation (Figs. 5.6 and 5.7). Furthermore in the same study DB anatomic reconstruction was found to be superior to SB reconstruction.

The above mentioned anatomic and biomechanical laboratory studies provided the basic science to safely start to introduce DB ACL reconstruction into clinical research. In chapters 9 and 10 two comparative studies between DB anatomic and SB ACL reconstruction were presented. In both of them the superiority of DB reconstruction in improving patients' satisfaction and knee stability was demonstrated at mid-term follow-up. Furthermore in Chapter 10 study the same technology to measure cadaver knees knee laxity in the biomechanics laboratory was employed on living awake patients and results, though preliminary, were comparable to those observed in the laboratory with DB anatomic reconstruction performing better than SB.

In summary, this thesis has one main experimental finding, i.e. that DB anatomic ACL reconstruction yields restoration of intact knee laxity and improved clinical outcomes, and one main research teaching, i.e. that the anatomic replication of a structure can restore its function if a complete multidisciplinary approach to its anatomy and physiology is performed, possibly by the same research team.

The latter concept is not new in orthopaedics. The superiority of anatomic reconstruction of the posterolateral knee structures has been demonstrated by the researchers of the Department of Orthopaedic Surgery of the University of Minnesota (USA), after a complete anatomic, biomechanical and clinical work (LaPrade, Johansen, Agel et al 2010; Griffith, Laprade, Coobs et al 2007; LaPrade, Morgan, Wentorf et al 2007; Sanchez, Sugalski LaPrade et al 2006).

Oxford (UK) researchers have demonstrated that anatomy restoration in the unicompartamental knee arthritis through the implantation of a unicondylar knee arthroplasty plus the reconstruction of the deficient ACL ensures excellent clinical results and restores intact knee kinematics (Pandit, Van Duren, Gallagher et al 2008; Pandit, Beard, Jenkins et al 2006).

Other anatomic reconstruction comprehensive research studies are being conducted elsewhere on different subjects. For instance the effectiveness of anatomic double bundle reconstruction of the posterior cruciate ligament (Apsingi, Nguyen, Bull et al 2008; Edwards, Bull, Amis 2007) and of the coraco-acromial ligaments is being tested (Costic, Labriola, Rodosky et al 2004; Jari, Costic, Rodosky et al 2004; Debski, Fenwick, Vangura et al 2003).

Although the experimental findings of this thesis were consistent and led to Level-I clinical evidence (Chapter 10) different fields of research are still open with ongoing projects and other studies are being conceived.

As to in-vivo kinematics, measurements are being obtained from a larger cohort of patients in order to verify the preliminary results. Furthermore the design of the splints is being improved in order to measure in vivo in awake patients the pivot shift phenomenon as well and overcome the subjectivity of the clinician rating. Some basic science research on pivot shift has been already performed by the same research team (Bull, Andersen, Basso et al 1999; Bull, Earnshaw, Smith et al 2002; Lie, Bull, Amis 2007). Further research will first focus on the understanding of its clear fine mechanism in relation to the ACL bundles, possibly through the definition of their different moment arms about the centres of rotation in abduction, flexion and tibial internal/external rotation, and then the new acquisitions will be exported in vivo.

As to the surgical technique a new device has been designed to improve hamstrings graft fixation. It consists of a small titanium plate and two bi-cortical screws (Fig. 11.6) which should ensure strong cortical fixation to the reconstruction. This fixation showed that both ACL bundle grafts can be fixed together (Chapter 5)



Figure 11.6: new DB hamstrings fixation device consisting of a plate and two bicortical screws.

Cyclic load tests are being conducted to compare the new fixation device to interference screw fixation on bovine bones (Fig. 11.7). Preliminary results are in favour of the new device (Fig. 11.8).

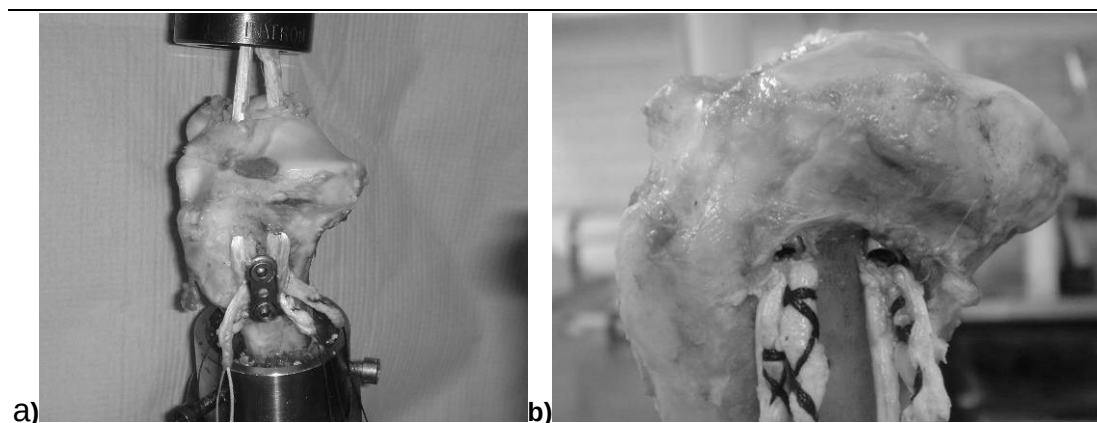


**Figure 11.7: a) new fixation device construct in a testing apparatus;
b) interference screws controls**

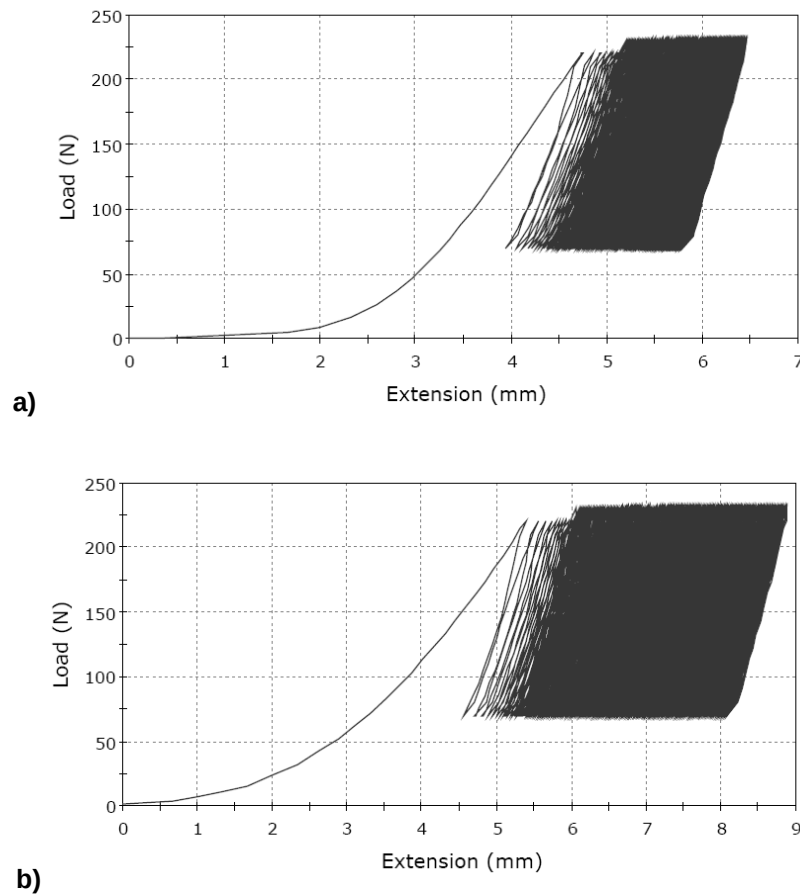


**Figure 11.8: a) load elongation graph from a plate test;
b) load elongation graph from an Interference screw test**

Finally, in the clinics, a new Level-I double blinded randomised clinical trial comparing DB anatomic ACL reconstruction with hamstrings graft fixed with the above described system and SB ACL reconstruction with a BPTB graft is starting.

In conclusion this thesis, through a multidisciplinary approach, has demonstrated the biomechanical and clinical superiority of DB ACL reconstruction in restoring intact knee laxity and patients' satisfaction. The thesis is part of a larger ongoing project involving several fields of research at different institutions in different countries.

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