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Anatomical single bundle anterior cruciate ligament reconstruction

Michael R. Carmont · Sven Scheffler · Tim Spalding · Jeremy Brown · Paul M. Sutton

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Abstract We present a review of the literature looking at the anatomy of the Anterior Cruciate Ligament, the biomechanical aspects of ACL reconstruction, review the outcomes of single and double bundle ACL reconstruction and present the current techniques for anatomic single bundle reconstruction.

Keywords Anatomical · Single bundle · Cruciate · Reconstruction · ACL

Introduction

According to the Scandinavian ACL registry ACL injuries occur in 6 per 1000 patients per year. Seventy percent are sustained during sporting activity and incidence rates of 85 per 100000 occur in the at risk group from 16 to 39 years. Injury rates are four times higher in females than males [1]. Over 100,000 ACL reconstructions are performed per year in the United States [2] making ACL reconstruction a common orthopaedic procedure.

The ultimate goal of Anterior Cruciate Ligament (ACL) reconstruction is the restoration of normal knee kinematics in patients with functionally unstable ACL deficient knees. It has been hypothesized that abnormal knee kinematics is one of the primary causes of the development of osteoarthritis (OA) after ACL reconstruction [3, 4] and from this it is hoped that anatomical ACL reconstruction will reduce the long-term incidence of OA.

Until recently the focus of anterior cruciate ligament reconstruction was to place a single bundle of graft tissue in an isometric position to restore knee function [5, 6]. Tunnel positions were chosen noting that the femoral tunnel has a major effect on the length-tension pattern of the reconstruction. In the 1990s the trans-tibial technique was developed as a quick reproducible method; the femoral tunnel is drilled through the tibial tunnel using an offset femoral drill guide so both tunnels are linked. During the follow up of these patients whilst they showed minimal antero-posterior translation based on Lachmans test and arthrometer assessment, they often still had a pivot glide to examination and reduced rotational stability.

With increasing research more has become understood of the anatomy of the ACL and non-anatomic femoral tunnel placement became recognised as one of the most common causes of failed ACL reconstruction. Anatomical studies have identified that the ACL is actually composed of two bundles: an antero-medial and a postero-lateral bundle, named according to their position on the tibial plateau. There is debate as to whether these form a continuum of fibres or two distinct bundles however most authors agree

M. R. Carmont (✉) · J. Brown · P. M. Sutton
The Northern General Hospital, Sheffield University Teaching Hospitals NHS Foundation Trust,
Sheffield, UK
e-mail: mcarmont@hotmail.com

J. Brown
e-mail: Jeremy.Brown@sth.nhs.uk

P. M. Sutton
e-mail: Paul.Sutton@sth.nhs.uk

S. Scheffler
Centre for Musculoskeletal Surgery, Charite Universitatsmedizin,
Berlin, Germany
e-mail: sven.scheffler@gmx.net

M. R. Carmont · T. Spalding
The University Hospitals of Coventry & Warwickshire NHS Trust,
Coventry, UK

T. Spalding
e-mail: tim@timspalding.com

that the ACL may be functionally separated into two bundles. Double bundle reconstruction first proposed in the 1980's [7, 8] was prompted by attempts to reconstruct both bundles and so improve rotational stability. Initial double bundle reconstruction was performed, with the femoral tunnels drilled through the tibia but accurate placement on the wall of the lateral femoral condyle proved difficult. The intact ACL anatomy was frequently not fully restored. The drilling of the femoral tunnel through the antero-medial portal has greatly increased the ability to independently choose specific femoral tunnel placement. Additionally substantial improvements in the knowledge of the exact morphology of the ACL insertion sites has lead to more anatomic double bundle techniques.

Whilst double bundle technique may improve the bundle appearance of the ACL, it increases the operating time in both the number of tunnels to be drilled, the placement of the tunnels and the operative complexity of passing and securing the two grafts. In addition it is known that 6% of reconstructions will re-rupture [9] with the same incidence in the contralateral knee. Having had two tunnels within the femur may leave larger bony voids within the lateral femoral condyle to fill during revision surgery.

Attention has returned to single bundle grafts placed anatomically using the anteromedial portal as a method of placing the femoral tunnel independent of the tibial tunnel.

We now present a review of the literature looking at the anatomy of the ACL, the biomechanical aspects of ACL reconstruction, review the outcomes of single and double bundle ACL reconstruction and present the current techniques for anatomic single bundle reconstruction.

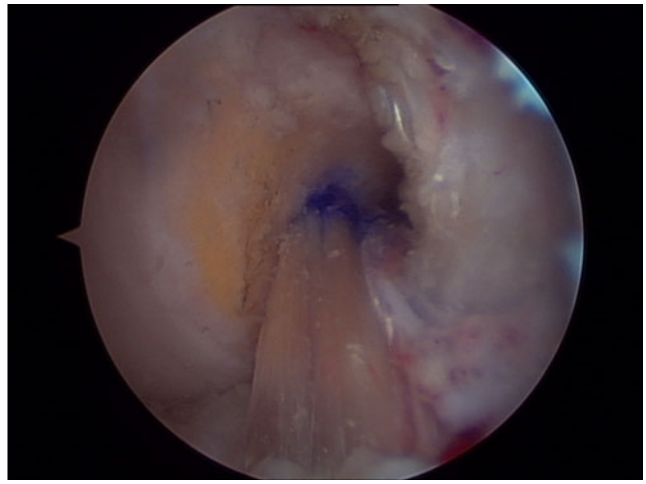

Fig. 1 Anatomical single bundle ACL reconstruction viewed through an anteromedial portal. The tunnel is positioned at the mid-condylar position using the ruler technique [65•]. The purple mark confirms that 25 mm of graft is within the femoral tunnel

Anatomy

Numerous cadaveric studies report on the anatomy of the femoral origin of the ACL [10–12]. It is now appreciated that the native ACL femoral insertion site is located along osseous landmarks on the posterior aspect of the medial wall of the lateral femoral condyle; termed the lateral intercondylar and bifurcate ridges (Fig. 1) [13]. The lateral intercondylar ridge corresponds to the feature termed the Residents Ridge reported by Clancy [14].

Identification of these ridges when present has been shown to be an accurate and reliable method to locate the native ACL femoral insertion site and the true entry point for the femoral tunnel [15]. Although these ridges have been identified in 97% of museum femur specimens [16], the presence of these ridges at arthroscopy on ACL deficient knees is however variable and they may not be seen [17]. Reports describe identifying the lateral intercondylar ridge in 100% of 60 knees at arthroscopy and the bifurcate ridge in 82% in one series [18]. Young active people may also place more strain on their ACLs and according to Wolf's law bone ridges may be preserved [14]. Van Eck et al. performed an arthroscopic case control study to compare the presence of ridges in sub acute and chronic ACL deficient knees. The lateral intercondylar ridge and lateral bifurcate ridges were present in 88% and 48% of knees in both groups respectively [19].

High resolution volume rendering CT scanning has allowed the critical bony landmarks relating to the anterior cruciate ligaments to be identified. In this descriptive laboratory study ACL fibres were present up to the roof of the notch and to within 3 to 3.5 mm of the articular surface posteriorly and inferiorly [20].

The attachment sites of the AM and PL bundles are generally considered to be oval with an area ranging from 65 mm^2 to 150 mm^2 [21, 22]. The attachment area of the AM bundle is larger than that of the PL bundle at a ratio of 3:2 [22]. The PL bundle is more distal than the AM bundle so that with the knee flexed to 100 ° the insertion sites are horizontal [23]. The ligament itself is three times smaller at its mid-substance compared with its insertion.

The variations of nomenclature between anatomical and arthroscopic positioning must be appreciated. Anatomical and radiological descriptions are based with the knee in full extension comprising of anterior posterior distal and proximal. Whereas arthroscopic descriptions are based on the arthroscopic view with the knee at 90 ° of flexion: high, low, shallow and deep [24].

The tibial insertion has also been increasingly appreciated and key landmarks are found on the tibial eminence similar to the lateral femoral wall. The eminence features 2 tubercles, the lateral tibial eminence and the medial tibial eminence separated by an intertubercular ridge. The medial condylar ridge extends anteriorly from the medial tubercle. The insertion of the ACL is from the fovea at the base of the intertubercular ridge to the posterior border of the lateral meniscus [25]. Fibers may extend up to the intertubercular ridge and the medial condylar ridge [10, 26].

The ACL inserts into a fovea anterior to the tibial eminence. In a cadaveric study the overall size of the tibial insertion was found to be a mean of 114 mm^2 with range 67–259 mm^2. In males the insertion was 15 mm long and in females slightly shorter at 14 mm. The AM bundle has a larger area (67 mm^2) than the PL bundle (52 mm^2). The centres of the bundle insertions are 5 mm apart [27, 28]. Ziegler found the ACL attachment centre was 7.5 mm medial to the anterior horn of the lateral meniscus and 13 mm anterior to the retroeminence ridge [29•].

The relative positions of the AM and PL bundles on the wall of the femoral condyle and the tibial plateau means that the bundles are crossed when the knee is flexed and become parallel when the knee moves into extension. These differing relations mean that different bundles have different effects on the stability of the knee during flexion and extension.

Biomechanical studies

According to the position of the knee, the AM and PL bundles have differing stabilizing effects. The anteromedial bundle is tighter in knee flexion and the posterolateral bundle is tighter in extension [30]. Cadaveric studies have shown that the AM bundle takes most of the load during anterior tibial translation at high flexion angles whereas the PL bundle resists 30–40% of the rotatory force at low flexion angles [31].

Clinical tests for anterior cruciate stability include the Lachmans test, the anterior drawer, the Pivot Shift test, the Losee test and the Slocum tests [32]. Although accurate in experienced hands these tests may be difficult to quantify. The development of arthrometer measurement however allows increasing accuracy for the assessment of ligament laxity.

These measurements allow the stability of cadaveric single (SB) and double bundle (DB) ACL reconstruction together with non-anatomic and anatomic tunnel placement to be compared. Non-anatomic grafts being placed in previously isometrically positioned tunnels deep within the notch and anatomic grafts being inserted specifically within the anatomic origin of the ACL.

Controlled laboratory studies have shown superiority of DB ACL reconstructions in restoring knee kinematics for both translations and rotations compared with single bundle reconstruction [31, 33–36]. Radford and Amis showed that DB reconstruction controlled anterior laxity better than single bundle across the range of knee flexion [34].

The group at the Hospital for Special Surgery have analysed the three dimensional motion of knees during a Lachman test and mechanized pivot shift testing in cadaveric specimens. There was no difference found between anatomical antero-medial SB and DB reconstructions with Lachmans test. During pivot shift testing greater anterior tibial translation was found during anatomical antero-medial SB and non-anatomical SB reconstructions compared to intact knee [37]. Kondo et al. found that double bundle reconstruction was better than non-anatomic single bundle however there was no difference compared to a laterally placed anatomical single bundle. They concluded that double bundle reconstruction may not offer a significant advantage over single bundle [38]. Ho et al. showed equal kinematics using central anatomic single bundle compared to double bundle reconstruction [39].

Voos et al. have recently emphasized the importance of careful placement with single bundle studies on cadaveric knees. Grafts placed in the antero-medial tibial footprint had less anterior tibial translation (ATT) with the Lachman and pivot shift maneuvers than knees with grafts placed in the posterolateral tibial footprint. They concluded that anteromedial placement on the tibia may reduce rotational instability when compared with more vertical configurations [40]. Whilst cadaveric biomechanical studies may give information about the effect of tunnel position after fixation, we need information on the functional aspects and return to physical activity following surgery with the goal of the alleviation of symptomatic instability and the avoidance of repeat knee injury.

Clinical outcomes

The outcomes following ACL reconstruction may be determined from subjective (Lysholm and Tegner) and objective clinical scores (IKDC, Knee Osteoarthritis Outcome Score KOOS), the requirement for revision surgery and the development of osteoarthritis. Given the biomechanical advantages of performing double bundle ACL reconstruction over non-anatomic single bundle reconstruction it is not surprising that there have been numerous clinical studies comparing double and single bundle ACL reconstruction [38, 41–47]. Several of these reveal improved anterior and rotational stability with DB reconstruction [38, 43, 45, 47] however many show no significant difference [42, 44, 46].

It is important to consider whether true anatomic or non-anatomic reconstructions are being performed during these comparisons [48, 49]. Yasuda has shown significantly improved outcome at 2 years for anatomical double bundle reconstruction over non-anatomic double bundle reconstruction [47]. It is only recently that the technique of performing an anatomic reconstruction using a trans-tibial technique has been reported [50]. Piasecki et al. however do comment that using this technique it is difficult to place a tunnel within the anatomic insertion and the compromise is to place the tibial tunnel more posterior to reach the anatomical femoral tunnel position.

Aglietti states that better results are achieved using an outside in compared to a trans-tibial DB ACL reconstruction [51]. In a randomized controlled study DB reconstructed patients had better VAS, final objective IKDC scores and improved knee stability than SB with a trend towards less pivot shift and more sports activities recovery. Notably 12% to 30% of ACL reconstructions demonstrated a pivot shift persists postoperatively [52].

Lewis performed a systematic review of single bundle ACL reconstruction outcomes: a base line assessment for consideration of double bundle techniques [53, 54]. Jarvela reported on outcomes at 2 years reporting improved knee kinematics post operatively for DB compared with SB reconstruction [41] however Siebold compared both SB and DB reconstructions and found no advantage in using the a DB technique [45]

In 2008 Meredick et al. performed a meta-analysis and found no difference between SB and DB ACL reconstruction [42]. Since this meta-analysis a few studies have compared lateralized or anatomic single bundle reconstructions with double bundle.

Anatomical single bundle versus anatomical double bundle anterior cruciate ligament reconstruction was compared using an electromagnetic measurement system at Kobe University in Japan. KT 1000 measurements, isokinetic peak muscle torque, heel height difference and Lysholm score at 1 year follow up showed no differences between either group. The EMS data did show that the anatomical double bundle ACL reconstruction tended to be biomechanically superior than the single bundle reconstruction but no difference in outcome measurement was observed [55].

Zaffagnini compared lateralized single bundle bone patellar tendon bone autograft with non-anatomical double bundle hamstring tendon autograft and showed significantly higher Tegner level, higher passive range of motion recovery, faster sport resumption, lower glide pivot shift phenomenon and lower re-intervention rate for DB hamstrings compared to the patellar tendon group [56]. This study introduces the confounding factor of graft selection by comparing bone-patellar tendon-bone versus hamstring graft.

Izawa has performed a cohort study comparing double bundle reconstruction performed through a trans-tibial technique using a tibial drill guide system with trans-tibial single bundle performed at 50 ° to the horizontal plane. Although a mechanized Slocum Anterolateral Rotational Instability test showed significant improvement there was no difference in Lysholm and Tegner scores, KT2000 and Pivot Shift testing [57].

The double-bundle surgical technique is considered complex, and more time consuming and technically difficult, precluding its widespread acceptance and adoption by ACL surgeons. All new techniques have been shown to have a learning curve. Snow and Stanish for example showed a reduced surgical time from 125 min to 65 min over a series of 10 patients following a change from a trans-tibial technique for DB reconstruction. CT scans showed that there was a tenancy to place tunnels too distal of the femur compared to their anatomical location [58].

The cost effectiveness of double bundle reconstruction compared to single bundle has been studied revealing that despite an upfront cost double bundle ACL reconstruction may be cost effective with an incremental cost effectiveness ratio of $6416 per quality adjusted life year [59].

Most certainly the theoretical gold standard is the restoration of normal anatomy with a double bundle reconstruction performed with tunnels for both bundles placed in their respective anatomical positions. Such surgery is complex and has a learning curve with the introduction of relatively large tunnels within the lateral femoral condyle using current graft fixation techniques. These defects potentially complicating revision surgery in those that re-rupture. Biomechanically double bundle reconstruction has been shown to improve knee stability but as yet improved clinical outcome over anatomic singe bundle reconstruction has yet to be conclusively proven.

Anatomical single bundle techniques

Over the last 10 years the benefits of a low tunnel placement on the arthroscopic view of the notch have become increasingly appreciated. It is still relatively common to describe the position of the femoral tunnel according to a clock face [60, 61]. Lower positions e.g. 2 o'clock, offer more rotational stability than higher e.g. 1 o'clock position [60]. This even extended to double bundle reconstruction where the centre of the anteromedial and posterolateral bundles being described as 1:40 and 3:10 positions respectively [22]. The clockface method clearly is subject to inter-observer interpretation, knee flexion angle and the position of the centre of the clockface varies between surgeons. The fact that the anterior aspect of the intercondylar notch is not circular also makes interpretation difficult.

Identifying the anatomy of the ACL origin has been recognized as the key to anatomical ACL reconstruction for some time [62–64]. Although the lateral intercondylar ridge and lateral bifurcate ridge have been described [13], they can be difficult to visualise [64].

Other techniques to determine the location of the ACL origin include intra-operative arthroscopic measurement and fluoroscopic imaging. Mid-condylar measuring techniques were first used by Watanabe and described by Kaseta et al. They noted that the center of the ACL was within 2 mm of an arthroscopic reference point located at the junction of a line drawn distally from the most proximal corner of the articular margin on the lateral wall of the notch and a perpendicular line drawn to the most posterior point of the condyle [65].

Bird et al. have recently described a mid-condylar measuring technique. The femoral tunnel being centred at a pick hole located at the mid point of the lateral femoral condyle from shallow to deep on the arthroscopic view with the knee at 90 °. The lowest point of the tunnel was 2 mm anterior to the distal femoral articular cartilage margin (Figure) [66•]. Using this method the centre of the femoral tunnel as measured on a grid popularized by Bernard and Hertel grid [67]. When this was placed on three dimensional CT scans the mean point was found to be only 1 mm away from the centre of the femoral insertion determined from the mean position reported in the literature. This method permits the preservation of soft tissue on the lateral wall, which may improve graft incorporation and so outcome [68]. Yasuda has similarly commented that the tunnel should be 5–6 mm shallow to the edge of the cartilage in the 1030 position [47].

The location of the femoral tunnel position according to radiographic criteria was studied by Bernard and Hertal and this method is subsequently used for the description of femoral tunnel location [65]. Their method involves the placement of a grid placed against Blumensaat's line on the true lateral post-operative radiograph and the comparison of varying tunnel positions according to the ordinates of the grid. Authors have used this method to successfully compare the position of the femoral tunnel [69]. Odensten recommends the tunnel is placed 24.8% from the lateral articular surface and 28.5% from the posterior edge of Blumensaats line [21]. Silva recently found the median difference of the distance between the centre of the femoral tunnel and the center of the AM and PL bundles along Blumensaat's line was 6 and 5% respectively. The height of the femoral condyle and the median difference of the distance between the centre of the femoral tunnel and the center of the AM and PL bundles was 0 and 31% respectively. The authors used a tibial tunnel angled 60–65° in the coronal plane [70].

Staubli and Rauschning have similarly looked at the location of the tibial tunnel on lateral radiographs noting that the anteromedial bundle is located at 30% and the posterolateral bundle 44% from anterior to posterior [71]. Use of 3D CT has been used to validate femoral tunnel position post operatively [18, 72, 73].

The use of intra-operative imaging fluoroscopy to locate the described tunnel starting points is possible but is both time consuming and makes the remainder of the operation more difficult due to cumbersome radiation protection gowns [74]. Intra-operative radiography also adds additional cost to the procedure.

The placement of the femoral bundles low down on the wall of the lateral femoral condyle has led to the development of new tunnel drilling methods. Harner described PL femoral tunnel placement in a low anterior position compared to the AM bundle by drilling through an antero-medial portal [75]. Care must be taken to avoid contact of the drill with the articular surface of the medial femoral condyle [76]. The use of flexible drilling systems may also improve safe tunnel position [77]. Surgeons may use two anteromedial portals: a high portal close to the patella tendon providing visualization and a second more medial portal just above the meniscus for instrumentation [78]. These independent drilling methods have been shown to produce tunnels with superior function compared with tunnels produced by conventional transtibial drilling methods [78, 79].

Controversy exists as to whether anatomical tunnel placement can be achieved using a transtibial tunnel drilling [80].

Piasecki recently compared two tibial entry points to determine whether the anatomical femoral origin of the ACL could be reached using a transtibial technique. In this paper a more proximal and medial entry point 15.9 mm distal to the joint line and 9.8 mm medial to the tibial tubercle allowed the insertion site to be reached. The authors conclude that femoral tunnels can be positioned in an anatomic manner however the starting point is at the limit of practical and offers little margin for error [50]. Strauss recently established that the use of a transtibial drilling technique resulted in a non-anatomic superior and posterior femoral tunnel [81].

When trans-tibial and antero-medial drilling techniques were compared transtibial tunnels were significantly more anterior and there was significantly more angulation towards the lateral condylar cortex for anteromedial portal drilling [82]. Dargel et al. concluded that AM portal drilling results in a tunnel, which may allow stabilisation for both anterior tibial translation and rotational instability.

Bedi and Altchek have modified antero-medial portal drilling with the use of a flexible guidewire and reaming system performing anatomic ACL reconstruction in over 100 "footprint" reconstructions with minimal intra-operative or postoperative complications [83].

The adoption of an anatomic approach to primary, revision and augmentation anterior cruciate ligament reconstruction also allows an intact bundle to be preserved so that only reconstruction of the deficient bundle may be performed [84].

The concept of complete footprint restoration has recently been suggested. This concept is based on the hypothesis that restoration of the biomechanical function of an ACL restored knee is a function of the reconstructed ACL insertion site area. The natural variations in insertion site morphology with length measurement between 8–21 mm. Small footprints up to 13 mm can be restored using anatomical single bundle reconstruction whereas larger double bundle grafts may be required for footprints of 16 mm or more [85•].

Conclusions

Anterior cruciate ligament reconstruction has progressed from the transtibial placment of isometric single bundle grafts through the complex surgery of double bundle reconstruction. The appreciation of the technical difficulty of double bundle reconstruction the lack of a clear advantage in clinical outcome and the improved awareness of the anatomy of the ACL insertion has led to a return to anatomical single bundle ACL reconstruction in the mid bundle position. The awareness of the anatomy of the ACL insertion is the key for reconstruction although double bundle techniques will continue to prove useful for specific cases of substantial rotational instability in large knee joints, revision and solitary bundle reconstruction for partial ACL injury.

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