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**Review of evolution of tunnel position in anterior cruciate ligament reconstruction**

Rayan F *et al.* Tunnel position in ACL reconstruction

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**Abstract**

Anterior cruciate ligament (ACL) rupture is one of the commonest knee sport injuries. The annual incidence of the ACL injury is between 100000-200000 in the United States. Worldwide around 400000 ACL reconstructions are performed in a year. The goal of ACL reconstruction is to restore the normal knee anatomy and kinesiology. The tibial and femoral tunnel placements are of primordial importance in achieving this outcome. Other factors that influence successful reconstruction are types of grafts, surgical techniques and rehabilitation programmes. A comprehensive understanding of ACL anatomy has led to the development of newer techniques supplemented by more robust biological and mechanical concepts. In this review we are mainly focussing on the evolution of tunnel placement in ACL reconstruction, focusing on three main categories, *i.e.*, anatomical, biological and clinical outcomes. The importance of tunnel placement in the success of ACL reconstruction is well researched. Definite clinical and functional data is lacking to establish the superiority of the single or double bundle reconstruction technique. While there is a trend towards the use of anteromedial portals for femoral tunnel placement, their clinical superiority over trans-tibial tunnels is yet to be established.

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**Key words:** Anterior cruciate ligament; Anatomy; Biomechanics; Isometry; Tunnel

**Core tip:** We are mainly focussing on the evolution of tunnel placement in anterior cruciate ligament (ACL) reconstruction especially on three main categories, *i.e.*, anatomical, biological and clinical outcomes. The importance of tunnel placement in the success of ACL reconstruction is well researched and still ongoing. Due to the nature of the intervention it is difficult to attain definite clinical and functional data to establish the superiority of the single or double bundle reconstruction technique.

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**ANTERIOR CRUCIATE LIGAMENT – ANATOMICAL PERSPECTIVE**

The anterior cruciate ligament (ACL) is an intracapsular but extra synovial structure. It is the primary static stabilizer in the anterior translation of the tibia in relation to the femur and helps in preventing extreme tibial rotations. The ACL originates from the posteromedial aspect of the lateral femoral condyle in the intercondylar notch and attaches to anterior aspect of the tibial plateau. The femoral attachment of the ACL is oriented along the long axis of femur. The centre of the ACL lies about 9 mm posterior to the intermeniscal ligament and 7-8 mm from the PCL, nearly 6 mm anterior to a projected line from the apex of the medial tibial eminence[[1](#_ENREF_1),[2](#_ENREF_2)]. The tibial attachment lies parallel to the anteroposterior axis of tibia.

The ACL is divided into two bundles based on their insertion on the tibial footprint, namely anteromedial (AM) and posterolateral (PL)[[3](#_ENREF_3)]. The two bundles were first described by Weber *et al*[[4](#_ENREF_4),[5](#_ENREF_5)]. These bundles are seen as early as in the fetal life[[6](#_ENREF_6)]. The AM and PL bundles differ in their length, width and the insertional area on femur and tibia. In 90 degrees of knee flexion, these insertion points are horizontal to each other whereas in extension, they are oriented vertically. The AM and PL bundles are oriented parallel in extension and change to being crossed in flexion. The average intra-articular length is 33 mm (range 22-41 mm). The width of ACL ranges from 7 to 17 mm with an average of about 11 mm. The average length of AM bundle is 33 mm and PL bundle is 18 mm. While the average cross-sectional area is 47 mm in males, it is about 37 mm in females[[3](#_ENREF_3)].

In knee flexion, the larger AM bundle tightens and PL bundle relaxes. In extension, the PL bundle tightens while the AM bundle relaxes. As different portions of the bundles tighten throughout the range of motion, the ACL remains functional throughout the range of motion[[7](#_ENREF_7)]. The principal blood supply to the ACL is from middle genicular artery, which is a branch of popliteal artery. It reaches ACL by piercing the posterior capsule[[7](#_ENREF_7)]. The inferomedial and inferolateral genicular arteries supply ACL from the fat pad. The posterior articular nerve, a branch of the tibial nerve, supplies the ACL. The ACL has proprioceptive nerve fibres, which helps protect the knee joint. There are several mechanoreceptors within the ACL, which contributes to proprioception[[8-12](#_ENREF_8)]. The ACL is mainly composed of highly organized matrix of Type I collagen1 which constitutes about 90% of the fibres and the rest is predominantly Type III collagen. As the ACL has inherent viscoelasticity, it can stretch and return to its normal resting length without suffering any significant structural damage[[7](#_ENREF_7)].

**EVOLUTION OF TUNNEL PLACEMENT IN ACL RECONSTRUCTION**

Incorrect positioning of either tibial or femoral tunnel has remained the most common reason for suboptimal outcome or failure of the ACL reconstruction[[13](#_ENREF_13),[14](#_ENREF_14)]. Anterior placement of femoral tunnel could lead to restriction of knee flexion and tightness of the graft in flexion. Placing the tibial tunnel slightly anteriorly may cause graft impingement subsequently leading to failure. Single bundle ACL reconstruction has been used successfully for the last few decades with good outcomes. It clearly has certain advantages in terms of surgical time, technical ease, low cost, fewer complications, ease of revision and less tunnel widening[[6](#_ENREF_6)]. But recent long term studies have shown the long term sequelae of arthritic changes and persistent instability (especially rotatory) and inability to return to previous level of activity[[15](#_ENREF_15),[16](#_ENREF_16)]. With the ever improving techniques in arthroscopic surgery, double bundle ACL reconstruction was recommended to reconstruct AM and PL bundles separately to imitate the normal anatomy of the native ACL, thus helping the restoring knee stability more effectively and theoretically eliminating the ‘Pivot Shift’. Recent studies have shown better biomechanical stability (AP and rotational) and clinical outcome with double bundle compared to single bundle ACL reconstruction[[17-20](#_ENREF_17)]. The double bundle ACL reconstruction may have the added advantage of better graft-bone healing because the increased graft-bone contact area[[21](#_ENREF_21)]. However, some studies have shown no difference in the clinical outcome between the single and double bundle ACL reconstruction and the controversy related to single and double bundle technique still remains[[5](#_ENREF_5),[6](#_ENREF_6),[18-20](#_ENREF_18),[22](#_ENREF_22)]. ACL has been reconstructed using various tunnel techniques (for example single tibial tunnel with single femoral tunnel, single tibial tunnel with double femoral tunnel or double tibial tunnel with double femoral tunnel). A survey among the 20 panellists worldwide suggested that one of the most common techniques used was 2 femoral and 2 tibial tunnels, hamstring graft being the most common graft. There was greater disparity among them about the AM bundles in femur but were consistent in their femoral AL bundles[[23](#_ENREF_23)].

Transtibial tunnel drilling often results in non-anatomic placement of the femoral tunnels[[24](#_ENREF_24)]. In the recent years, the transtibial tunnel drilling has been increasingly replaced by anatomic femoral tunnel as such tunnels are believed to offer increased rotational stability, translational and tensioning patterns similar to the native ACL[[25](#_ENREF_25),[26](#_ENREF_26)]. There is evidence is the literature about the high revision rates in non-anatomical placement of ACL[[27](#_ENREF_27)]. This could represent inadequacy of transtibial tunnel drilling technique for placement within the native femoral and tibial footprints of the ACL[[28](#_ENREF_28),[29](#_ENREF_29)]. Placing the femoral tunnel in the anatomical femoral footprint of the ACL results in closer knee joint kinematics closer to the intact knee than a tunnel suited for the best graft isometry[[30](#_ENREF_30)]. Integrity of the posterior cortex of the femur is of paramount importance (at least 2 mm of the posterior rim of the femoral tunnel to the posterior edge of the notch roof) for a successful outcome of the surgery.

**CONCEPT OF ISOMETRY**

The ligaments in the body are taut and maintain their length during the range of movements of the joint concerned. This cannot be strictly being applicable to all the ligaments in the body. This “concept of isometry” is important in ACL, as full ROM can be achieved without causing significant long term deformation. Isometry in ACL does not exist as there is no one point on femur that maintains a fixed distance from a single point on the tibia during the range of motion of the knee. The AM bundle tightens in flexion and slack in extension. The fibres of AM bundle which has relatively vertical attachment on the femur are more isometric.

In order to achieve graft isometry the optimal position of the femoral tunnel was thought be 11’o clock (right) or 1 clock position (with respect to the apex of the notch, modified femoral clock wall model ) which places the graft high and posterior in the lateral femoral condyle[[18](#_ENREF_18)]. (However, the o’clock terminology is not favoured by everybody, as they argue that femoral notch is a three dimensional structure and placing the tunnel according the clock may lead to non-anatomical placement). If the graft is placed anterior to this position, it will be tight in flexion, thus restricting the full ROM. If the graft is placed posterior to this position, the graft will tighten with knee extension[[31](#_ENREF_31)].

**CONCEPT OF ANATOMICAL TUNNELS**

While the initial literature proposed ACL reconstruction with graft isometry, the subsequent literature proved that “graft isometry” is not the most crucial factor in ACL reconstruction but it is the graft placement in the “anatomical attachment” of the ACL[[32](#_ENREF_32)]. As the anatomical placement of the femoral tunnel better resists the rotational force it may reduce the risk of later osteoarthritis[[25](#_ENREF_25),[33](#_ENREF_33)]. The footprint of the femoral attachment of the ACL and “Lateral Intercondylar Ridge” (Resident’s Ridge) serve as useful landmarks for the placement of femoral tunnel. It is better visualized with a 70 degree scope (helps in avoiding the parallax error while using 30 degree arthroscopic camera) and through anteromedial portal[[34-36](#_ENREF_34)] (Table1).

Resident’s Ridge is commonly located just anterior to the femoral attachment of the ACL. Awareness of ‘Resident’s Ridge’ is important as it can mislead the inexperienced surgeons to place the femoral tunnels in incorrect positions[[34](#_ENREF_34)]. “Lateral intercondylar ridge” and the “lateral bifurcate ridge” serve as the bony landmarks for the femoral attachments[[35](#_ENREF_35)]. At knee in 90 degree flexion, lateral intercondylar ridge runs from proximal to distal through the entire length of ACL foot print. No ACL fibres attach superior to the ridge. Lateral bifurcate ridge when present, separates the AM and the PL bundles femoral insertions and it runs almost perpendicular to the lateral intercondylar ridge. In the absence of consistent intra-operative soft tissue or osseous land marks, “Ruler method” can be used to determine the mid-bundle femoral tunnel positioning[[37](#_ENREF_37)]. Radiographic quadrant method using Blumensaat’s line can be used to locate optimal femoral footprint of ACL[[38](#_ENREF_38)].

**TIBIAL TUNNEL**

Correct placement of the tibial tunnel is vital for successful surgery and to avoid complications such as anterior knee pain, loss of knee extension, instability and graft impingement. An ideal position for the tibial tunnel would at the centre of the footprint of the ACL in the intercondylar area. This position is located using multiple bony and osseous landmarks[[1](#_ENREF_1),[2](#_ENREF_2),[39](#_ENREF_39),[40](#_ENREF_40)]. The outside entry in to the tibial tunnel is often at 4 cm from tibial joint line and 2 cm medial to the tibial tubercle. Several radiographic methods have been employed to locate the ideal place for a tibial tunnel[[41](#_ENREF_41),[42](#_ENREF_42)]. An ideal tibial tunnel should avoid the PCL impingement. This can be done by performing notchplasty, drilling the tibial tunnel at about 60-65 degree angle with respect to medial joint line and by placing the lateral edge of the tibial tunnel through the lateral tibial spine[[6](#_ENREF_6)].

**BIOMECHANICAL STUDIES ON TUNNEL POSITIONING**

There have been several biomechanical studies that have studied the effects of different tunnel positioning and graft placement in ACL reconstruction (table 2). These studies have mainly compared graft placement in the femur at the standard 11-o’clock more vertical position for the right knee (or 1-o’clock position for the left knee) with grafts placed at the more oblique or lateral 9.30 to 10-o’clock position[[43](#_ENREF_43)-45]. Other studies have analysed the effect of anatomic graft placement and isometric positions[[30](#_ENREF_30),46,47].

**Ten-O’CLOCK OR 11-O’CLOCK POSITION?**

ACL reconstruction should re-create the coronal and sagittal obliquity of the graft similar to the orientation of the intact ACL. Increasing the coronal plane obliquity of the femoral tunnel has gained popularity over the last decade as biomechanical studies have shown it to be superior to vertical tunnel placement[[43](#_ENREF_43),[45](#_ENREF_45)]. Loh *et al*[[43](#_ENREF_43)] tested 10 human cadaveric knees with reconstructed bone-patella tendon-bone graft at the 10 and 11-o’clock position. They compared two external loading conditions: anterior tibial load of 134N with the knee at full extension, 15°, 30°, 60° and 90°of flexion and a combined rotatory load of 10 Nm valgus and 5 Nm internal tibial torque with the knee at 15° and 30°of flexion. The authors concluded while both the tunnel positions were equally effective under an anterior tibial load, the 10-o’clock position more effectively resists rotatory loads when compared to the 11-o’clock position[[43](#_ENREF_43)]. These findings were further supported by a similar experimental study by Scopp *et al*[[45](#_ENREF_45)]. The authors measured the anterior tibial translation with a 100 N load and external and internal tibial rotation with a 6.5 Nm torque applied at 30° and 90° of flexion in 10 matched pairs of human cadaveric knees. They found that the group with the standard 30° from vertical reconstruction had significantly more laxity in internal rotation, therefore concluding that ACL reconstruction using the oblique 60° femoral tunnel more closely restored normal knee kinematics[[45](#_ENREF_45)].

Markolf *et al*[[44](#_ENREF_44)] however questioned the rationale for placing an oblique femoral tunnel. They compared the abilities of an ACL graft placed at the 11-o’clock and 9:30- to 10-o’clock femoral tunnel positions to limit tibial rotation and lateral tibial plateau displacement during a simulated pivot shift event. For each specimen, the authors found a unique combination of valgus moment and iliotibial band tension that caused the ACL deficient knee to pivot. The same combination of loads was then applied to the ACL reconstructed knee. They believed that their test methodology better simulates the pivot shift that occurs during clinical examination compared to the previous two studies by Loh *et al*[43] and Scoop *et al*[[44](#_ENREF_44)]. They concluded that moving the femoral tunnel from the standard location to a more oblique position in the notch did not significantly alter pivot shift kinematics.

**ANATOMIC *VS* ISOMETRIC GRAFT PLACEMENT?**

The anatomical footprint of the ACL is located in a different position than one positioned for best graft isometry. Femoral tunnel position for best isometry (over-the-top position) is located high in the femoral notch whist the anatomical footprint of the ACL is located lower[[30](#_ENREF_30)]. The concept of isometric graft placements is to avoid changes in graft length and tension during knee flexion and extension to avoid graft failure by overstretching[[26](#_ENREF_26),[48](#_ENREF_48)]. However, there are concerns that the isometric placement of the graft will result in a more vertically orientated graft in the sagittal plane and therefore less effective at resisting motions in the transverse plane. Furthermore, basic science studies have shown that the normal ACL is not isometric with the anteromedial bundle of the ACL experiencing higher stress during flexion and the posterolateral bundle experiencing higher stress during extension[[49](#_ENREF_49)].

Several studies have shown that positioning the femoral tunnel position inside the anatomical footprint of the ACL results in knee kinematics closer to the intact knee than does a tunnel position located for best isometry[[30](#_ENREF_30),46]. Musahl *et al*[30] tested 10 cadaveric knees in response to a 134 N anterior load and a combined 10 Nm valgus and 5 Nm internal rotation load and found a significant difference between these 2 tunnel positions[[30](#_ENREF_30)]. In another study, Driscoll *et al*[[46](#_ENREF_46)]compared femoral tunnels that were reamed through the anteromedial portal and centred alternatively in either the AM portions of the femoral footprint or the centre of the femoral footprint[[46](#_ENREF_46)]. They concluded that a femoral tunnel positioned in the true anatomic centre of the femoral origin of the ACL may improve rotatory stability without sacrificing anterior stability[[46](#_ENREF_46)]. These findings were further supported in a more recent study conducted by Abebe *et al*[[47](#_ENREF_47)]who compared femoral tunnels that was placed near the anterior and proximal border of the ACL and another near the centre of the ACL footprint. The results of their study showed that grafts placed antero proximally on the femur were in a more vertical orientation and therefore less likely to provide sufficient restrain. Normal orientation of the graft was better achieved with anatomical placement of the graft ultimately resulting in a more stable knee[[47](#_ENREF_47)].

**TIBIAL TUNNEL POSITIONING**

Bedi *et al*[[50](#_ENREF_50)] evaluated the effect of tibial tunnel position on restoration of knee kinematics after ACL reconstruction. Ten paired cadaveric knees were subjected to standardized Lachman and mechanized pivot shift examination[[50](#_ENREF_50)]. Biomechanical testing was performed on ACL reconstruction using 3 tibial tunnel positions- over the top (non-anatomic positioning), anterior footprint and posterior footprint with a standard central femoral tunnel position at the femoral ACL footprint. The results of their study demonstrated that tibial tunnel positioning of a single bundle ACL graft has a critical influence on knee stability and impingement. Anterior positing of the tibial tunnel either in the over the top position or at the anterior foot print produces favourable kinematics than posterior positioning of the tibial tunnel. However, the authors warned that these biomechanical advantages have a risk of causing secondary notch impingement leading to graft attrition and failure. Therefore, the authors recommended that the tibial tunnel should be positioned in the central aspect of the native ACL footprint may offer the best compromise.

**CLINICAL STUDIES ON TUNNEL POSITIONING**

There have been relatively fewer studies looking at the clinical outcomes of different tunnel positions in ACL reconstruction. Anatomic *vs* non-anatomic tunnel placement is still debated though there is some evidence to support the anatomic approach. Most studies compare the two main techniques for drilling the femoral tunnel, the transtibial technique and the use of a separate anteromedial portal (Table 3) Overall, most studies agree that the anteromedial portal technique allows a more anatomic femoral tunnel position when compared to the transtibial technique[[51](#_ENREF_51),[52](#_ENREF_52)]. Some studies have compared the clinical outcomes of high (1 o’clock/11 o’clock) femoral tunnel position *vs* low (2 o’clock/10 o’clock) position[[53](#_ENREF_53)-55].

**ANATOMIC *VS* NON-ANATOMIC FEMORAL TUNNEL POSITION**

Excellent short-term outcomes using the anatomic femoral tunnel have been reported objectively (IKDC Knee score, Lachman and pivot shift tests and a KT **arthrometer**, Tegner score, WOMAC score, IKDC score), subjectively (Lysholm score) and in terms of knee stability with double bundle ACL reconstruction using the anteromedial portal technique as well as in a comparison study looking at bone-patellar tendon-bone (BPTB) and hamstring grafts[51,[56](#_ENREF_56)]. 3D-CT was used to assess tunnel position in these two cases. Studies have also documented worse clinical outcomes and poorer IKDC scores with nonanatomical positions[[57](#_ENREF_57)-[59](#_ENREF_58)]. Anatomical femoral tunnel positions may be associated with earlier return to sports on previous Tegner score level and better functional outcomes at 12 month follow-up[[60](#_ENREF_60)].

**TRANSTIBIAL *VS* ANTEROMEDIAL PORTAL TECHNIQUES FOR THE FEMORAL TUNNEL**

There is still debate as to whether this changes the clinical outcomes for the patient. No difference in functional outcome was demonstrated by two large cohort studies[[61](#_ENREF_61),62]. Moreover with the transtibial technique, there were significantly higher odds of the knee requiring repeat ipsilateral knee surgery[[61](#_ENREF_61)]. The latter finding is also supported by, a Danish Knee Ligament Reconstruction Registry study (RR 2.04, 95%CI: 1.39, 2.91)[[63](#_ENREF_63)]. However, some benefits of AMP have been documented such as increased stability with a higher Lysholm score, better lateral movement functional tests at 3 and 6 mo, significantly lower recovery time from surgery to walking without crutches, return to normal life, return to jogging and significantly higher activity level at 3-5 and 6-10 year follow-up[[52](#_ENREF_52),[64](#_ENREF_64),[65](#_ENREF_65)]. Seo *et al*[[66](#_ENREF_66)] (2013) compared the “outside in” technique, to the transtibial technique for single bundle ACL reconstruction. They found with this technique, a more anatomical femoral tunnel placement was achieved with better knee joint rotational stability on pivot shift test and subjectively on the IKDC questionnaire items for instability. There was however no difference on the Lysholm score, range of movement measurements, Lachman tests or Tegner activity scale[[66](#_ENREF_66)].

***High (1 o’clock/11 o’clock) vs low (2 o’clock/10 o’clock) femoral tunnel position***

The low tunnel has been shown to have similar or significantly better intraoperative internal rotational stability at 0 and 30 degrees of knee flexion compared to high position[[53](#_ENREF_53)-55]. However, the functional benefit of this has been supported by one study and refuted by others[[53](#_ENREF_53)-55]. There was no significant difference between the groups in stability tests or functional scores at final follow-up.

**TIBIAL TUNNEL POSITION**

Few studies in the literature which focus primarily on the clinical outcomes of the tibial tunnel position in ACL reconstruction. Anterior placement of the tibial tunnel inside the footprint has shown better anterior knee stability, pivot shift and side to side stability tests and knee flexion but no difference in loss of knee extension or graft failure at minimum 2 year follow-up[[67](#_ENREF_67),[68](#_ENREF_68)]. The intermeniscal ligament and Parsons knob should be used as the landmarks for the tibial tunnel for ACL reconstruction. Maximum favourable results were achieved through 35%-46% anteroposterior placement of the tibial tunnel[[69](#_ENREF_69)]. However that too anterior (anterior 25% of the tibial plateau) placement of the tibial tunnel results in poor clinical outcomes[[69](#_ENREF_69)]. However, the effect of tibial tunnel position on the clinical outcome (measured by IKDC score) is not established[[59](#_ENREF_59),[69](#_ENREF_69)]. Overall, the literature suggests that more anatomical placement of both the tibial and femoral tunnels confers better stability to the knee and some benefit in terms of functional outcomes. To achieve this for femoral tunnel, the anteromedial portal or outside-in techniques have been suggested to be better.

In conclusion, our understanding of ACL injuries and their reconstruction continues to evolve. The importance of tunnel placement in the success of ACL reconstruction is well established. Definite clinical and functional data is lacking to establish the superiority of the single or double bundle reconstruction technique. While there is a trend towards the use of anteromedial portals for femoral tunnel, their clinical superiority over trans tibial tunnels is yet to be established. Any change in clinical practice of anatomical bundles, tunnel position or placement for ACL reconstruction must follow long-term clinical study results to establish definite advantages of newer techniques or bio-mechanical theories.

**REFERENCES**

1 **Petersen W**, Tillmann B. [Anatomy and function of the anterior cruciate ligament]. *Orthopade* 2002; **31**: 710-718 [PMID: 12426749]

2 **Ferretti M**, Doca D, Ingham SM, Cohen M, Fu FH. Bony and soft tissue landmarks of the ACL tibial insertion site: an anatomical study. *Knee Surg Sports Traumatol Arthrosc* 2012; **20**: 62-68 [PMID: 21710110 DOI: 10.1007/s00167-011-1592-z]

3 **Giuliani JR**, Kilcoyne KG, Rue JP. Anterior cruciate ligament anatomy: a review of the anteromedial and posterolateral bundles. *J Knee Surg* 2009; **22**: 148-154 [PMID: 19476182]

4 **Weber W,** Weber EF. Mechanik der menschlichen gehwerkzeuge: Eine anatomisch-physiologische untersuchung. Dietrich, 1836

5 **Longo UG**, Buchmann S, Franceschetti E, Maffulli N, Denaro V. A systematic review of single-bundle versus double-bundle anterior cruciate ligament reconstruction. *Br Med Bull* 2012; **103**: 147-168 [PMID: 21990019 DOI: 10.1093/bmb/ldr044]

6 **Prodromos CC**, Fu FH, Howell SM, Johnson DH, Lawhorn K. Controversies in soft-tissue anterior cruciate ligament reconstruction: grafts, bundles, tunnels, fixation, and harvest. *J Am Acad Orthop Surg* 2008; **16**: 376-384 [PMID: 18611995]

7 **Larson RL**, Tailon M. Anterior Cruciate Ligament Insufficiency: Principles of Treatment. *J Am Acad Orthop Surg* 1994; **2**: 26-35 [PMID: 10708991]

8 **Schultz RA**, Miller DC, Kerr CS, Micheli L. Mechanoreceptors in human cruciate ligaments. A histological study. *J Bone Joint Surg Am* 1984; **66**: 1072-1076 [PMID: 6207177]

9 **Schutte MJ**, Dabezies EJ, Zimny ML, Happel LT. Neural anatomy of the human anterior cruciate ligament. *J Bone Joint Surg Am* 1987; **69**: 243-247 [PMID: 3805085]

10 **Ochi M**, Iwasa J, Uchio Y, Adachi N, Sumen Y. The regeneration of sensory neurones in the reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Br* 1999; **81**: 902-906 [PMID: 10530860]

11 **Adachi N**, Ochi M, Uchio Y, Iwasa J, Ryoke K, Kuriwaka M. Mechanoreceptors in the anterior cruciate ligament contribute to the joint position sense. *Acta Orthop Scand* 2002; **73**: 330-334 [PMID: 12143983 DOI: 10.1080/000164702320155356]

12 **Georgoulis AD**, Pappa L, Moebius U, Malamou-Mitsi V, Pappa S, Papageorgiou CO, Agnantis NJ, Soucacos PN. The presence of proprioceptive mechanoreceptors in the remnants of the ruptured ACL as a possible source of re-innervation of the ACL autograft. *Knee Surg Sports Traumatol Arthrosc* 2001; **9**: 364-368 [PMID: 11734875 DOI: 10.1007/s001670100240]

13 **Khalfayan EE**, Sharkey PF, Alexander AH, Bruckner JD, Bynum EB. The relationship between tunnel placement and clinical results after anterior cruciate ligament reconstruction. *Am J Sports Med* 1996; **24**: 335-341 [PMID: 8734885]

14 **Pinczewski LA**, Salmon LJ, Jackson WF, von Bormann RB, Haslam PG, Tashiro S. Radiological landmarks for placement of the tunnels in single-bundle reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Br* 2008; **90**: 172-179 [PMID: 18256083 DOI: 10.1302/0301-620X.90B2.20104]

15 **Pinczewski LA**, Lyman J, Salmon LJ, Russell VJ, Roe J, Linklater J. A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. *Am J Sports Med* 2007; **35**: 564-574 [PMID: 17261567 DOI: 10.1177/0363546506296042]

16 **Biau DJ**, Tournoux C, Katsahian S, Schranz P, Nizard R. ACL reconstruction: a meta-analysis of functional scores. *Clin Orthop Relat Res* 2007; **458**: 180-187 [PMID: 17308473 DOI: 10.1097/BLO.0b013e31803dcd6b]

17 **Mae T**, Shino K, Miyama T, Shinjo H, Ochi T, Yoshikawa H, Fujie H. Single- versus two-femoral socket anterior cruciate ligament reconstruction technique: Biomechanical analysis using a robotic simulator. *Arthroscopy* 2001; **17**: 708-716 [PMID: 11536089]

18 **Siebold R**, Dehler C, Ellert T. Prospective randomized comparison of double-bundle versus single-bundle anterior cruciate ligament reconstruction. *Arthroscopy* 2008; **24**: 137-145 [PMID: 18237696 DOI: 10.1016/j.arthro.2007.11.013]

19 **Järvelä T**, Moisala AS, Sihvonen R, Järvelä S, Kannus P, Järvinen M. Double-bundle anterior cruciate ligament reconstruction using hamstring autografts and bioabsorbable interference screw fixation: prospective, randomized, clinical study with 2-year results. *Am J Sports Med* 2008; **36**: 290-297 [PMID: 17940145 DOI: 10.1177/0363546507308360]

20 **Muneta T**, Sekiya I, Yagishita K, Ogiuchi T, Yamamoto H, Shinomiya K. Two-bundle reconstruction of the anterior cruciate ligament using semitendinosus tendon with endobuttons: operative technique and preliminary results. *Arthroscopy* 1999; **15**: 618-624 [PMID: 10495178 DOI: 10.1053/ar.1999.v15.0150611]

21 **Hamada M**, Shino K, Horibe S, Mitsuoka T, Miyama T, Shiozaki Y, Mae T. Single- versus bi-socket anterior cruciate ligament reconstruction using autogenous multiple-stranded hamstring tendons with endoButton femoral fixation: A prospective study. *Arthroscopy* 2001; **17**: 801-807 [PMID: 11600976]

22 **Kondo E**, Yasuda K, Azuma H, Tanabe Y, Yagi T. Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients. *Am J Sports Med* 2008; **36**: 1675-1687 [PMID: 18490472 DOI: 10.1177/0363546508317123]

23 **Zantop T**, Kubo S, Petersen W, Musahl V, Fu FH. Current techniques in anatomic anterior cruciate ligament reconstruction. *Arthroscopy* 2007; **23**: 938-947 [PMID: 17868832 DOI: 10.1016/j.arthro.2007.04.009]

24 **Strauss EJ**, Barker JU, McGill K, Cole BJ, Bach BR, Verma NN. Can anatomic femoral tunnel placement be achieved using a transtibial technique for hamstring anterior cruciate ligament reconstruction? *Am J Sports Med* 2011; **39**: 1263-1269 [PMID: 21335354 DOI: 10.1177/0363546510395488]

25 **Lee MC**, Seong SC, Lee S, Chang CB, Park YK, Jo H, Kim CH. Vertical femoral tunnel placement results in rotational knee laxity after anterior cruciate ligament reconstruction. *Arthroscopy* 2007; **23**: 771-778 [PMID: 17637414 DOI: S0749-8063(07)00516-6]

26 **Zavras TD**, Race A, Amis AA. The effect of femoral attachment location on anterior cruciate ligament reconstruction: graft tension patterns and restoration of normal anterior-posterior laxity patterns. *Knee Surg Sports Traumatol Arthrosc* 2005; **13**: 92-100 [PMID: 15756613 DOI: 10.1007/s00167-004-0541-5]

27 **Marchant BG**, Noyes FR, Barber-Westin SD, Fleckenstein C. Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. *Am J Sports Med* 2010; **38**: 1987-1996 [PMID: 20702859 DOI: 10.1177/0363546510372797]

28 **Abebe ES**, Moorman CT, Dziedzic TS, Spritzer CE, Cothran RL, Taylor DC, Garrett WE, DeFrate LE. Femoral tunnel placement during anterior cruciate ligament reconstruction: an in vivo imaging analysis comparing transtibial and 2-incision tibial tunnel-independent techniques. *Am J Sports Med* 2009; **37**: 1904-1911 [PMID: 19687514 DOI: 10.1177/0363546509340768]

29 **Alentorn-Geli E**, Samitier G, Alvarez P, Steinbacher G, Cugat R. Anteromedial portal versus transtibial drilling techniques in ACL reconstruction: a blinded cross-sectional study at two- to five-year follow-up. *Int Orthop* 2010; **34**: 747-754 [PMID: 20401753 DOI: 10.1007/s00264-010-1000-1]

30 **Musahl V**, Plakseychuk A, VanScyoc A, Sasaki T, Debski RE, McMahon PJ, Fu FH. Varying femoral tunnels between the anatomical footprint and isometric positions: effect on kinematics of the anterior cruciate ligament-reconstructed knee. *Am J Sports Med* 2005; **33**: 712-718 [PMID: 15722268 DOI: 10.1177/0363546504271747]

31 **Hefzy MS**, Grood ES, Noyes FR. Factors affecting the region of most isometric femoral attachments. Part II: The anterior cruciate ligament. *Am J Sports Med* 1989; **17**: 208-216 [PMID: 2667378]

32 **Garofalo R**, Moretti B, Kombot C, Moretti L, Mouhsine E. Femoral tunnel placement in anterior cruciate ligament reconstruction: rationale of the two incision technique. *J Orthop Surg Res* 2007; **2**: 10 [PMID: 17511888 DOI: 10.1186/1749-799X-2-10]

33 **Ajuied A**, Wong F, Smith C, Norris M, Earnshaw P, Back D, Davies A. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. *Am J Sports Med* 2014; **42**: 2242-2252 [PMID: 24214929 DOI: 10.1177/0363546513508376]

34 **Hutchinson MR**, Ash SA. Resident's ridge: assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. *Arthroscopy* 2003; **19**: 931-935 [PMID: 14608310]

35 **Ferretti M**, Ekdahl M, Shen W, Fu FH. Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. *Arthroscopy* 2007; **23**: 1218-1225 [PMID: 17986410 DOI: 10.1016/j.arthro.2007.09.008]

36 **Purnell ML**, Larson AI, Clancy W. Anterior cruciate ligament insertions on the tibia and femur and their relationships to critical bony landmarks using high-resolution volume-rendering computed tomography. *Am J Sports Med* 2008; **36**: 2083-2090 [PMID: 18663150 DOI: 10.1177/0363546508319896]

37 **Bird JH**, Carmont MR, Dhillon M, Smith N, Brown C, Thompson P, Spalding T. Validation of a new technique to determine midbundle femoral tunnel position in anterior cruciate ligament reconstruction using 3-dimensional computed tomography analysis. *Arthroscopy* 2011; **27**: 1259-1267 [PMID: 21741796 DOI: 10.1016/j.arthro.2011.03.077]

38 **Bernard M**, Hertel P, Hornung H, Cierpinski T. Femoral insertion of the ACL. Radiographic quadrant method. *Am J Knee Surg* 1997; **10**: 14-21; discussion 21-2 [PMID: 9051173]

39 **Morgan CD**, Kalman VR, Grawl DM. Definitive landmarks for reproducible tibial tunnel placement in anterior cruciate ligament reconstruction. *Arthroscopy* 1995; **11**: 275-288 [PMID: 7632302 DOI: 10.1016/0749-8063(95)90003-9]

40 **Colombet P**, Robinson J, Christel P, Franceschi JP, Djian P, Bellier G, Sbihi A. Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. *Arthroscopy* 2006; **22**: 984-992 [PMID: 16952729 DOI: 10.1016/j.arthro.2006.04.102]

41 **Amis AA**, Jakob RP. Anterior cruciate ligament graft positioning, tensioning and twisting. *Knee Surg Sports Traumatol Arthrosc* 1998; **6** Suppl 1: S2-12 [PMID: 9608456 DOI: 10.1007/s001670050215]

42 **Stäubli HU**, Rauschning W. Tibial attachment area of the anterior cruciate ligament in the extended knee position. Anatomy and cryosections in vitro complemented by magnetic resonance arthrography in vivo. *Knee Surg Sports Traumatol Arthrosc* 1994; **2**: 138-146 [PMID: 7584195 DOI: 10.1007/BF01467915]

43 **Loh JC**, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL. Knee stability and graft function following anterior cruciate ligament reconstruction: Comparison between 11 o'clock and 10 o'clock femoral tunnel placement. 2002 Richard O'Connor Award paper. *Arthroscopy* 2003; **19**: 297-304 [PMID: 12627155 DOI: 10.1053/jars.2003.50084]

44 **Markolf KL**, Jackson SR, McAllister DR. A comparison of 11 o'clock versus oblique femoral tunnels in the anterior cruciate ligament-reconstructed knee: knee kinematics during a simulated pivot test. *Am J Sports Med* 2010; **38**: 912-917 [PMID: 20308433 DOI: 10.1177/0363546509358321]

45 **Scopp JM**, Jasper LE, Belkoff SM, Moorman CT. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. *Arthroscopy* 2004; **20**: 294-299 [PMID: 15007318 DOI: 10.1016/j.arthro.2004.01.001]

46 **Driscoll MD**, Isabell GP, Conditt MA, Ismaily SK, Jupiter DC, Noble PC, Lowe WR. Comparison of 2 femoral tunnel locations in anatomic single-bundle anterior cruciate ligament reconstruction: a biomechanical study. *Arthroscopy* 2012; **28**: 1481-1489 [PMID: 22796141 DOI: 10.1016/j.arthro.2012.03.019]

47 **Abebe ES**, Kim JP, Utturkar GM, Taylor DC, Spritzer CE, Moorman CT, Garrett WE, DeFrate LE. The effect of femoral tunnel placement on ACL graft orientation and length during in vivo knee flexion. *J Biomech* 2011; **44**: 1914-1920 [PMID: 21570688 DOI: 10.1016/j.jbiomech.2011.04.030]

48 **Fu FH**, Bennett CH, Lattermann C, Ma CB. Current trends in anterior cruciate ligament reconstruction. Part 1: Biology and biomechanics of reconstruction. *Am J Sports Med* 1999; **27**: 821-830 [PMID: 10569374]

49 **Gerich TG**, Cassim A, Lattermann C, Lobenhoffer HP. Pullout strength of tibial graft fixation in anterior cruciate ligament replacement with a patellar tendon graft: interference screw versus staple fixation in human knees. *Knee Surg Sports Traumatol Arthrosc* 1997; **5**: 84-88 [PMID: 9228314 DOI: 10.1007/s001670050032]

50 **Bedi A**, Maak T, Musahl V, Citak M, O'Loughlin PF, Choi D, Pearle AD. Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: is the tibial tunnel position most important? *Am J Sports Med* 2011; **39**: 366-373 [PMID: 21173195 DOI: 10.1177/0363546510388157]

51 **Taketomi S**, Inui H, Nakamura K, Hirota J, Sanada T, Masuda H, Takeda H, Tanaka S, Nakagawa T. Clinical outcome of anatomic double-bundle ACL reconstruction and 3D CT model-based validation of femoral socket aperture position. *Knee Surg Sports Traumatol Arthrosc* 2014; **22**: 2194-2201 [PMID: 24085109]

52 **Noh JH**, Roh YH, Yang BG, Yi SR, Lee SY. Femoral tunnel position on conventional magnetic resonance imaging after anterior cruciate ligament reconstruction in young men: transtibial technique versus anteromedial portal technique. *Arthroscopy* 2013; **29**: 882-890 [PMID: 23538044 DOI: 10.1016/j.arthro.2013.01.025]

53 **Seon JK**, Park SJ, Lee KB, Seo HY, Kim MS, Song EK. In vivo stability and clinical comparison of anterior cruciate ligament reconstruction using low or high femoral tunnel positions. *Am J Sports Med* 2011; **39**: 127-133 [PMID: 20847223 DOI: 10.1177/0363546510377417]

54 **Park JK**, Song EK, Seon JK. Comparison of intraoperative stability in ACL reconstruction based on femoral tunnel positions. *Orthopedics* 2010; **33**: 94-97 [PMID: 20954639 DOI: 10.3928/01477447-20100510-60]

55 **Jepsen CF**, Lundberg-Jensen AK, Faunoe P. Does the position of the femoral tunnel affect the laxity or clinical outcome of the anterior cruciate ligament-reconstructed knee? A clinical, prospective, randomized, double-blind study. *Arthroscopy* 2007; **23**: 1326-1333 [PMID: 18063177 DOI: 10.1016/j.arthro.2007.09.010]

56 **Sadoghi P**, Kröpfl A, Jansson V, Müller PE, Pietschmann MF, Fischmeister MF. Impact of tibial and femoral tunnel position on clinical results after anterior cruciate ligament reconstruction. *Arthroscopy* 2011; **27**: 355-364 [PMID: 21144694 DOI: 10.1016/j.arthro.2010.08.015]

57 **Abebe ES**, Utturkar GM, Taylor DC, Spritzer CE, Kim JP, Moorman CT, Garrett WE, DeFrate LE. The effects of femoral graft placement on in vivo knee kinematics after anterior cruciate ligament reconstruction. *J Biomech* 2011; **44**: 924-929 [PMID: 21227425 DOI: 10.1016/j.jbiomech.2010.11.028]

58 **Hosseini A**, Lodhia P, Van de Velde SK, Asnis PD, Zarins B, Gill TJ, Li G. Tunnel position and graft orientation in failed anterior cruciate ligament reconstruction: a clinical and imaging analysis. *Int Orthop* 2012; **36**: 845-852 [PMID: 21826407 DOI: 10.1007/s00264-011-1333-4]

59 **Behrend H**, Stutz G, Kessler MA, Rukavina A, Giesinger K, Kuster MS. Tunnel placement in anterior cruciate ligament (ACL) reconstruction: quality control in a teaching hospital. *Knee Surg Sports Traumatol Arthrosc* 2006; **14**: 1159-1165 [PMID: 16951973 DOI: 10.1007/s00167-006-0186-7]

60 **Fernandes TL**, Fregni F, Weaver K, Pedrinelli A, Camanho GL, Hernandez AJ. The influence of femoral tunnel position in single-bundle ACL reconstruction on functional outcomes and return to sports. *Knee Surg Sports Traumatol Arthrosc* 2014; **22**: 97-103 [PMID: 23132410 DOI: 10.1007/s00167-012-2288-8]

61 **Duffee A**, Magnussen RA, Pedroza AD, Flanigan DC, Kaeding CC. Transtibial ACL femoral tunnel preparation increases odds of repeat ipsilateral knee surgery. *J Bone Joint Surg Am* 2013; **95**: 2035-2042 [PMID: 24257662 DOI: 10.2106/JBJS.M.00187]

62 **Franceschi F**, Papalia R, Rizzello G, Del Buono A, Maffulli N, Denaro V. Anteromedial portal versus transtibial drilling techniques in anterior cruciate ligament reconstruction: any clinical relevance? A retrospective comparative study. *Arthroscopy* 2013; **29**: 1330-1337 [PMID: 23906273 DOI: 10.1016/j.arthro.2013.05.020]

63 **Rahr-Wagner L**, Thillemann TM, Pedersen AB, Lind MC. Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Register. *Arthroscopy* 2013; **29**: 98-105 [PMID: 23276417 DOI: 10.1016/j.arthro.2012.09.009]

64 **Koutras G**, Papadopoulos P, Terzidis IP, Gigis I, Pappas E. Short-term functional and clinical outcomes after ACL reconstruction with hamstrings autograft: transtibial versus anteromedial portal technique. *Knee Surg Sports Traumatol Arthrosc* 2013; **21**: 1904-1909 [PMID: 23203338 DOI: 10.1007/s00167-012-2323-9]

65 **Alentorn-Geli E**, Lajara F, Samitier G, Cugat R. The transtibial versus the anteromedial portal technique in the arthroscopic bone-patellar tendon-bone anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2010; **18**: 1013-1037 [PMID: 19902178 DOI: 10.1007/s00167-009-0964-0]

66 **Seo SS**, Kim CW, Kim JG, Jin SY. Clinical results comparing transtibial technique and outside in technique in single bundle anterior cruciate ligament reconstruction. *Knee Surg Relat Res* 2013; **25**: 133-140 [PMID: 24032102 DOI: 10.5792/ksrr.2013.25.3.133]

67 **Ohsawa T**, Kimura M, Hagiwara K, Yorifuji H, Takagishi K. Clinical and second-look arthroscopic study comparing 2 tibial landmarks for tunnel insertions during double-bundle ACL reconstruction with a minimum 2-year follow-up. *Am J Sports Med* 2012; **40**: 2479-2486 [PMID: 22962294 DOI: 10.1177/0363546512458257]

68 **Hatayama K**, Terauchi M, Saito K, Higuchi H, Yanagisawa S, Takagishi K. The importance of tibial tunnel placement in anatomic double-bundle anterior cruciate ligament reconstruction. *Arthroscopy* 2013; **29**: 1072-1078 [PMID: 23571132 DOI: 10.1016/j.arthro.2013.02.003]

69 **Avadhani A**, Rao PS, Rao SK. Effect of tibial tunnel position on arthroscopically assisted anterior cruciate ligament reconstruction using bone-patellar tendon-bone grafts: a prospective study. *Singapore Med J* 2010; **51**: 413-417 [PMID: 20593146]

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**Table 1 Anatomy and evolution summary**

|  |  |  |
| --- | --- | --- |
| AuRef. | Study type | Results / Conclusion |
| Petersen *et al*[1] | Anatomical | Describes the anatomy of ACL with histology. Describes definite landmarks of ACL attachments |
| Ferretti *et al*[2] | Cadaveric | The medial tibial eminence and the intermeniscal ligament may be used as landmarks to guide the correct tunnel placement in an anatomical ACL reconstruction |
| Schultz *et al*[8] | Histological | In this first histological demonstration of mechanoreceptors in human ACL, It seemed likely that mechanoreceptors provide proprioceptive information and contribute to reflexes inhibiting injurious movements of the knee |
| Schutte *et al*[9] | Histological | Three morphological types of mechanoreceptors and free nerve-endings were identified: two of the slow-adapting Ruffini type and the third, a rapidly adapting Pacinian corpuscle. Rapidly adapting receptors signal motion and slow-adapting receptors subserve speed and acceleration. Free nerve-endings, which are responsible for pain, were also identified within the ligament. These neural elements comprise 1 per cent of the area of the anterior cruciate ligament |
| Adachi *et al*[11] | Histological | Positive correlation between the number of mechanoreceptors and accuracy of the joint position sense, suggesting that proprioceptive function of the ACL is related to the number of mechanoreceptors. Recommended preserving ACL remnants during ACL reconstruction |
| Georgoulis *et al*[12] | Anatomical and histological | In patients with an ACL remnant adapted to the PCL, mechanoreceptors exist even 3 yr after injury |
| Mae *et al*[17] | Cross over trial using cadaveric laboratory study | The ACL reconstruction via 2 femoral sockets using quadrupled hamstring tendons provides better anterior-posterior stability compared with the conventional reconstruction using a single socket |
| Strauss *et al*[24] | Descriptive laboratory study | During hamstring ACL reconstructions, the constraints imposed by a coupled drilling technique result in nonanatomic femoral tunnels that are superior and posterior to the native femoral insertion. Clinical relevance: Anatomic femoral tunnel placement during hamstring ACL reconstructions may not be possible using a coupled, transtibial drilling approach |
| Zavras *et al*[26] | Controlled laboratory study | Laxity was restored best by grafts tensioned to a mean of 9 ± 14 N, positioned isometrically and 3 mm posterior to the isometric point. Their tension remained low until terminal extension. Grafts 3 mm anterior to the isometric point caused significant overconstraint, and had higher tension beyond 80 degrees knee flexion |
| Musahl *et al*[30] | Controlled laboratory study | Neither femoral tunnel position restores normal kinematics of the intact knee. A femoral tunnel placed inside the anatomical footprint of the ACL results in knee kinematics closer to the intact knee than does a tunnel position located for best graft isometry |
| Siebold *et al*[18] | Cadaveric Dissection.  Laboratory study | Clinical relevance: This study provides an anatomic description of the femoral AM and PL insertions including gender differences, landmarks, and arthroscopic orientation models for DB bone tunnel placement |
| Hefzy *et al*[31] | Cadaveric | Study found that altering the femoral attachment had a much larger effect than had altering the tibial attachment. The axis of the 2 mm region was nearly proximal-distal in orientation and located near the center of the ACL’s femoral insertion. Attachments located anterior to the axis moved away from the tibial attachment with flexion, whereas attachments located posterior to the axis moved toward the tibia |
| Hutchinson *et al*[34] | Cadaveric | The phenomenon of “resident’s ridge” is accounted for by a distinctive change in slope of the femoral notch roof that occurs just anterior to the femoral attachment of the ACL. The density change apparent at the time of notchplasty is probably caused by the transition between normal cortical thickness just anterior to the ACL and the cortical thickness of the ACL attachment. No distinctive increased cortical thickness can be identified as “resident’s ridge” |
| Ferretti *et al*[35] | Histological and Cadaveric anatomic study | The ACL femoral attachment has a unique topography with a constant presence of the lateral intercondylar ridge and often an osseous ridge between AM and PL femoral attachment, the lateral bifurcate ridge. CLINICAL RELEVANCE: These findings may assist surgeons to perform ACL surgery in a more anatomic fashion |
| Purnell *et al*[36] | Descriptive cadaveric study | CLINICAL RELEVANCE: Bony landmarks can be used to aid in anatomical anterior cruciate ligament reconstruction |
| Bernard *et al*[38] | Cadaveric Anatomic study | By using this radiographic quadrant method combined with fluoroscopic control during surgery, authors were able to reinsert the ACL at its anatomic insertion site. This method is independent of variation in knee size or film-focus distance, easy to handle, and reproducible. |
| Colombet *et al*[40] | Cadaveric study | The Retro Eminence Ridge provides an easily identifiable and accurate reference point that can be used clinically. On a lateral radiograph, the positions of the tibial attachments can be referenced to Amis and Jakob's line. This method, different from Blumensaat's line, is independent of knee flexion |
| Amis *et al*[41] |  | A study of knee anatomy and graft placement concluded that the tibial attachment must be posterior enough to avoid graft impingement against the femur, and methods to attain this were presented |

ACL: Anterior cruciate ligament.

**Table 2 Biomechanics summary**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Ref. | Study type | Femoral tunnel positioning | Anatomic or isometric  graft placement | Tibial tunnel positioning | Results |
| Loh *et al*[43] | Controlled laboratory study | Reconstructed bone-patella tendon-bone graft at the 10 and 11-o’clock position | - | - | Both the tunnel positions were equally effective under an anterior tibial load, the 10-o’clock position more effectively resists rotatory loads when compared to the 11-o’clock position |
| Scopp *et al*[45] | Controlled laboratory study | Reconstructed bone-patella tendon-bone graft at standard or oblique tunnel position | - | - | The group with the standard 30° from vertical reconstruction had significantly more laxity in internal rotation. The oblique 60° femoral tunnel more closely restored normal knee kinematics. |
| Markolf *et al*[44] | Controlled laboratory study | Compared the ACL graft placed at the 11-o’clock and 9:30- to 10-o’clock femoral tunnel positions during a simulated pivot shift event | - | - | There were no significant differences in tibial rotations or tibial plateau displacements during the pivot shift between standard and oblique femoral tunnels |
| Musahl *et al*[30] | Controlled laboratory study | - | Tested cadaveric knees in response to a 134 N anterior load and a combined 10 Nm valgus and 5 Nm internal rotation load | - | A femoral tunnel placed inside the anatomical footprint of the ACL results in knee kinematics closer to the intact knee than does a tunnel position located for best graft isometry |
| Driscoll *et al*[46] | Controlled laboratory study | - | Compared femoral tunnels that were reamed through the anteromedial portal and centred alternatively in either the AM portions of the femoral footprint or the centre of the femoral footprint |  | Femoral tunnel positioned in the true anatomic centre of the femoral origin of the ACL may improve rotatory stability without sacrificing anterior stability |
| Abebe *et al*[47] | Controlled laboratory study | - | Compared femoral tunnels that was placed near the anterior and proximal border of the ACL and another near the centre of the ACL footprint | - | Grafts placed anteroproximally on the femur were in a more vertical orientation and therefore less likely to provide sufficient restrain. Normal orientation of the graft was better achieved with anatomical placement of the graft ultimately resulting in a more stable knee |
| Bedi *et al*[50] | Controlled laboratory study | - | - | Evaluated the effect of 3 tibial tunnel positions on restoration of knee kinematics after ACL reconstruction: over the top (non-anatomic positioning), anterior footprint and posterior footprint with a standard central femoral tunnel position at the femoral ACL footprint | Anterior positing of the tibial tunnel either in the over the top position or at the anterior foot print produces favourable kinematics than posterior positioning of the tibial tunnel. However, there is a risk of causing secondary notch impingement leading to graft attrition and failure |

**Table3 Clinical studies summary**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Ref. | Year | Study type | Study size | Graft type | Femoral tunnel positioning | Tibial tunnel positioning | Follow-up time | Outcome measures | Results |
| Adebe *et al*[57] | 2011 | Retrospective Cohort | 22 patients | Hamstring and (BPTB) | Anatomic *vs*  Non-anatomic | - | 6-36 mo | Tibial translation and rotation | Anatomic tunnel more stable in terms of anterior and medial translation and internal rotation |
| Alentorn-Geli  *et al*[65] | 2010 | Cross-sectional comparative | 47 patients | BPTB | Transtibial *vs* anteromedial portal techniques | - | 2-5 yr | IKDC score; knee stability; ROM; one-leg hop test; mid-quadriceps circumference; VAS for satisfaction with surgery; Lysholm score; Tegner score; SF-12 | From AMP technique, significantly lower recovery time from surgery to walking without crutches, return to normal life, return to jogging, training and play. Significantly better knee stability values but no difference in other functional scores surgery |
| Avadhani  *et al*[69] | 2010 | Prospective cohort | 41 patients | BPTB | - | AP position of tunnel | Minimum 2 yr | IKDC score; Modified Lysholm score | Placing the tibial tunnel in the anterior 25% of the tibial plateau was associated with poor knee outcomes |
| Behrend *et al*[59] | 2006 | Retrospective cohort | 50 patients | BPTB | Position assessed using quadrant method of Bernard and Hertel | Position assessed using criteria of Staubli and Rauschnig | Mean 19 mo | IKDC score | More anterior the femoral canal, highly significant correlation with poorer IKDC score. Position of the tibial tunnel had no statistically significant effect on IKDC score |
| Duffee *et al*[61] | 2013 [6] | Prospective cohort | 436 patients | Hamstring and BPTB | Transtibial *vs* anteromedial portal techniques | - | 6 yr | Knee injury and osteoarthritis outcomes score (KOOS) | No difference between the techniques in terms of predicting functional outcome with KOOS |
| Fernandes  *et al*[60] | 2014 | Prospective cohort | 86 patients | Hamstring and BPTB | Anteromedial footprint (anatomic) and high anteromedial position | - | 6 and 12 mo | IKDC score; Tegner score; Lysholm scale; return to sports | Femoral tunnel positions at AM footprint and high AM position associated with earlier return to sports on previous Tegner score level and better functional outcomes at 12 mo |
| Franceschi  *et al*[62] | 2013 | Retrospective cohort | 94 patients | Hamstring | Transtibial *vs* anteromedial portal techniques | - | Minimum 5 yr | IKDC score; Lysholm scale; KT-1000 arthrometer; Lachman test; Pivot shift test; radiographic assessment | No difference between the two techniques in terms of functional scores (Lysholm and IKDC) though the anteromedial portal technique provided better rotational and anterior translational stability |
| Hatayama *et al*[68] | 2013 | Prospective cohort | 60 patients | Hamstring | - | AP position of tibial tunnel | 2 yr | Pivot shift test; stress radiographs; 2nd. look arthroscopy | Anterior placement of the tibial tunnel inside the footprint led to better anterior knee stability |
| Hosseini *et al*[58] | 2012 | Retrospective cohort | 26 patients | Hamstring, BPTB and allograft | Non-anatomic | Non-anatomic | - | Patients undergoing revision ACL surgery: MRI based 3D modelling | Both the tibial and femoral tunnel positions in the failed ACLR were non-anatomic compared to native ACL values |
| Jepsen *et al*[55] | 2007 | Prospective randomised trial | 60 patients | Hamstring | High (1 o’clock) *vs* Low (2 o’clock) positions | - | 1 yr | Laxity; IKDC Evaluation and Examination forms; radiograph assessment | No significant difference in the laxity at 25 degrees and 70 degrees or scores on the IKDC examination form. Significant difference in the scores on the IKDC evaluation form |
| Koutras *et al*[64] | 2013 | Prospective cohort | 51 patients | Hamstring | Transtibial *vs* anteromedial portal techniques | - | 3 and 6 mo | Lysholm score; isokinetic tests; functional tests | AMP technique had significantly better suggesting a quicker return to function and performance |
| Noh *et al*[52] | 2013 | Prospective randomised trial | 61 patients | Allograft | Transtibial *vs* anteromedial portal techniques | - | Mean 30.2 mo | Lachman test; pivot shift test; IKDC score; Lysholm score; Tegner activity scale; radiograph and MRI assessment | AMP technique resulted in a more posterior femoral tunnel position than the transtibial (TT) technique and knees with this technique were more stable with a higher Lysholm score |
| Ohsawa *et al*[67] | 2012 | Retrospective cohort | 121 patients | Hamstring | - | Posterior tibial landmark *vs* anterior tibia landmark | Minimum 2 yr | 3D CT; 2nd. look arthroscopy + EUA; Lachman, pivot shift and side-side stability tests; Lysholm score | Pivot shift and side to side stability tests and knee flexion were significantly better in the anterior landmark group |
| Park *et al*[54] | 2010 | Cross-sectional | 70 patients | Allograft | High (1 o’clock) *vs* Low (2 o’clock) positions | - | Intraoperative | Intraoperative anterior and rotational knee stability at differing degrees of flexion | The low femoral tunnel group showed significantly better intraoperative internal rotational stability at 0° and 30° of flexion |
| Rahr-Wagner *et al*[63] | 2013 | Prospective cohort | 9239 patients | - | Transtibial *vs* anteromedial technique | - | 4 yr | Need for revision; pivot-shift and instrumented objective test | Increased risk of revision ACL surgery when using the AM technique compared with the TT technique |
| Sadoghi *et al*[56] | 2011 | Prospective cohort | 53 knees | Hamstring and BPTB | Anatomic *vs* non-anatomic | Anatomic *vs* non-anatomic | 1 yr | 3D CT; Tegner score;WOMAC score; IKDC score; KT-1000 arthrometer measurements; pivot-shift test | Significantly superior clinical outcome in anatomic ACL reconstructions in terms of higher clinical scores (Tegner and IKDC), higher anterior posterior stability, and less pivot shift |
| Seon *et al*[53] | 2011 | Prospective cohort | 58 patients | Allograft | High (1 o’clock) *vs* Low (2 o’clock) positions | - | Minimum 2 yr | Lysholm; Tegner; Clinical & radiographic stability | Low tunnel group had significantly better internal rotational stability at 0 and 30 degrees of knee flexion |
| Seo *et al*[66] | 2013 | Retrospective cohort | 89 patients | Allograft | Transtibial *vs* “Outside in” techniques | - | Minimum 1 yr | 3D CT; pivot-shift; Lachman; IKDC; Lysholm; Tegner; ROM | A more anatomical femoral tunnel with better knee joint rotational stability on pivot shift test |
| Taketomi *et al*[51] | 2013 | Case series | 34 patients | Hamstring | Anatomic | - | 2 yr | Lysholm score; IKDC score; KT-2000 arthrometer; Lachman test; Reverse pivot-shift test | Excellent short-term using the anatomic femoral tunnel objectively, subjectively and in terms of knee stability |