

Review of evolution of tunnel position in anterior cruciate ligament 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.

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

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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^[1,2]. 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]. The two bundles were first described by Weber *et al*^[4] and Longo *et al*^[5]. These bundles are seen as early as in the fetal life^[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].

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]. 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]. 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]. The ACL is mainly composed of highly organized matrix of type I collagen 1 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].

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^[13,14]. 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]. 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^[15,16]. 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 (antero-posterior and rotational) and clinical outcome with double bundle compared to single bundle ACL reconstruction^[17-20]. The double bundle ACL reconstruction may have the added advantage of better graft-bone healing because the increased graft-bone contact area^[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^[5,6,18-20,22]. 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 antero-lateral bundles^[23].

Transtibial tunnel drilling often results in non-anatomic placement of the femoral tunnels^[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^[25,26]. There is evidence in the literature about the high revision rates in non-anatomical placement of ACL^[27]. This could represent inadequacy of transtibial tunnel drilling technique for placement within the native femoral and tibial footprints of the

ACL^[28,29]. 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]. 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 range of movements (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 o'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]. (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].

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]. As the anatomical placement of the femoral tunnel better resists the rotational force it may reduce the risk of later osteoarthritis^[25,33]. 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] (Table 1).

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]. "Lateral intercondylar ridge"

and the "lateral bifurcate ridge" serve as the bony landmarks for the femoral attachments^[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]. Radiographic quadrant method using Blumensaat's line can be used to locate optimal femoral footprint of ACL^[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^[1,2,39,40]. 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^[41,42]. 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].

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^[43-45]. Other studies have analysed the effect of anatomic graft placement and isometric positions^[30,46,47].

TEN-O'CLOCK OR ELEVEN-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^[43,45]. Loh *et al*^[43] tested 10 human cadaveric knees with

Table 1 Anatomy and evolution summary

Ref.	Study type	Results/conclusion
Petersen <i>et al</i> ^[11]	Anatomical	Describes the anatomy of ACL with histology. Describes definite landmarks of ACL attachments
Ferretti <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 percent of the area of the anterior cruciate ligament
Adachi <i>et al</i> ^[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 <i>et al</i> ^[12]	Anatomical and histological	In patients with an ACL remnant adapted to the PCL, mechanoreceptors exist even 3 yr after injury
Mae <i>et al</i> ^[17]	Cross over trial using cadaveric laboratory study	The ACL reconstruction <i>via</i> 2 femoral sockets using quadrupled hamstring tendons provides better anterior-posterior stability compared with the conventional reconstruction using a single socket
Strauss <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[36]	Descriptive cadaveric study	Clinical relevance: Bony landmarks can be used to aid in anatomical anterior cruciate ligament reconstruction
Bernard <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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; AM: Anteromedial; PL: Posterolateral.

Table 2 Biomechanics summary

Ref.	Study type	Femoral tunnel positioning	Anatomic or isometric graft placement	Tibial tunnel positioning	Results
Loh <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 <i>et al</i> ^[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 restraint. Normal orientation of the graft was better achieved with anatomical placement of the graft ultimately resulting in a more stable knee
Bedi <i>et al</i> ^[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

ACL: Anterior cruciate ligament; AM: Anteromedial.

reconstructed bone-patella tendon-bone graft at the 10 and 11-o'clock position. They compared two external loading conditions: anterior tibial load of 134 N 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]. These findings were further supported by a similar experimental study by Scopp

et al^[45]. The authors measured the anterior tibial translation with a 100N 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].

Markolf *et al*^[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 Scopp *et al*^[45]. 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 whilst the anatomical footprint of the ACL is located lower^[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^[26,48]. 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].

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^[30,46]. 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]. In another study, Driscoll *et al*^[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]. 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]. These findings were further supported in a more recent study conducted by Abebe *et al*^[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 restraint. Normal orientation of the graft was better achieved with anatomical placement of the graft ultimately resulting in a more stable knee^[47].

TIBIAL TUNNEL POSITIONING

Bedi *et al*^[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]. 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 positioning 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^[51,52]. Some studies have compared the

Table 3 Clinical studies summary

Ref.	Year	Study type	Study size	Graft type	Femoral tunnel positioning	Tibial tunnel positioning	Follow-up time	Outcome measures	Results
Adebe <i>et al</i> ^[57]	2011	Retrospective cohort	22 patients	Hamstring and (BPTB)	Anatomic <i>vs</i> 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 <i>et al</i> ^[65]	2010	Cross-sectional comparative	47 patients	BPTB	Transstibial <i>vs</i> 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 <i>et al</i> ^[60]	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 <i>et al</i> ^[69]	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 <i>et al</i> ^[61]	2013 ^[6]	Prospective cohort	436 patients	Hamstring and BPTB	Transstibial <i>vs</i> anteromedial portal techniques	-	6 yr	KOOS	No difference between the techniques in terms of predicting functional outcome with KOOS
Fernandes <i>et al</i> ^[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 <i>et al</i> ^[62]	2013	Retrospective cohort	94 patients	Hamstring	Transstibial <i>vs</i> 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 <i>et al</i> ^[68]	2013	Prospective cohort	60 patients	Hamstring	-	AP position of tibial tunnel	2 yr	Pivot shift test; stress radiographs; 2 nd look arthroscopy	Anterior placement of the tibial tunnel inside the footprint led to better anterior knee stability
Hosseini <i>et al</i> ^[68]	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 <i>et al</i> ^[65]	2007	Prospective randomised trial	60 patients	Hamstring	High (1 o'clock) <i>vs</i> 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 <i>et al</i> ^[64]	2013	Prospective cohort	51 patients	Hamstring	Transstibial <i>vs</i> 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 <i>et al</i> ^[62]	2013	Prospective randomised trial	61 patients	Allograft	Transstibial <i>vs</i> 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 TT technique and knees with this technique were more stable with a higher lysholm score

Ohsawa <i>et al</i> ^[67]	2012	Retrospective cohort	121 patients	Hamstring	-	Posterior tibial landmark vs anterior tibia landmark	Minimum 2 yr	3D CT; 2 nd 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 <i>et al</i> ^[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 <i>et al</i> ^[65]	2013	Prospective cohort	9239 patients	-	Trans tibial 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 IT technique
Sadoghi <i>et al</i> ^[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 (tegrer and IKDC), higher anterior posterior stability, and less pivot shift
Seon <i>et al</i> ^[53]	2011	Prospective cohort	58 patients	Allograft	High (1 o'clock) vs low (2 o'clock) positions	-	Minimum 2 yr	Lysholm; Tegner; Clinical and radiographic stability	Low tunnel group had significantly better internal rotational stability at 0 and 30 degrees of knee flexion
Seo <i>et al</i> ^[66]	2013	Retrospective cohort	89 patients	Allograft	Trans tibial 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 <i>et al</i> ^[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 anatomical femoral tunnel objectively, subjectively and in terms of knee stability

ACL: Anterior cruciate ligament; AM: Anteromedial; TT: Trans tibial; KOOS: Knee injury and osteoarthritis outcomes score; ACLR: Anterior cruciate ligament reconstruction; SF-12: Short form 12; VAS: Visual analogue scale; AP: Anter posterior; IT: Trans tibial; AMP: Antero medial portal; ROM: Range of movements.

clinical outcomes of high (1 o'clock/11 o'clock) femoral tunnel position vs low (2 o'clock/10 o'clock) position^[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 and hamstring grafts^[51,56]. 3D-computed tomography was used to assess tunnel position in these two cases. Studies have also documented worse clinical outcomes and poorer IKDC scores with nonanatomical positions^[57-59]. Anatomical femoral tunnel positions may be associated with earlier return to sports on previous Tegner score level and better functional outcomes at 12 mo follow-up^[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^[61,62]. Moreover with the trans tibial technique, there were significantly higher odds of the knee requiring repeat ipsilateral knee surgery^[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]. 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^[52,64,65]. Seo *et al*^[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].

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^[53-55]. However, the functional benefit of this has been supported by one study and refuted by others^[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^[67,68]. 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]. However that too anterior (anterior 25% of the tibial plateau) placement of the tibial tunnel results in poor clinical outcomes^[69]. However, the effect of tibial tunnel position on the clinical outcome (measured by IKDC score) is not established^[59,69]. 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 biomechanical theories.

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