Current Concepts Review

Anatomic anterior cruciate ligament reconstruction: Freddie Fu's paradigm

Michael A. Fox, MD*, Ian D. Engler, MD, Balint T. Zsidai, MD, Jonathan D. Hughes, MD, Volker Musahl, MD

Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, PA, 15213, USA

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ABSTRACT

Anterior cruciate ligament (ACL) reconstruction techniques have evolved over the past four decades. There is evidence that non-anatomic reconstruction techniques, such as traditional transtibial drilling, fail to recreate the native anatomy of the ACL, which can lead to increased rotatory knee instability, revision risk, and post-traumatic osteoarthritis. Anatomic ACL reconstruction has emerged as the gold standard, with the goal of restoring the patient's native anatomy and knee kinematics. This review will summarise the relevant anatomy, modern anatomic ACL reconstruction techniques, and literature supporting anatomic ACL reconstruction as the new paradigm.

Level of evidence: Level V, review article.

Current concepts:

- Anatomic anterior cruciate ligament (ACL) reconstruction aims to restore the individual patient's anatomy and has emerged as the gold standard in treatment of ACL injuries.
- Preoperative planning and consideration of the native knee anatomy is essential for appropriate graft selection and tunnel placement.
- Non-anatomic ACL reconstruction techniques increases the risk for numerous adverse outcomes including residual instability and surgical failure.

Future perspectives:

More long-term and high-quality outcomes studies will help in determining what techniques produce the best outcomes, and in which patient populations. Further investigation is needed to inform decisions regarding graft choice, anterolateral augmentation, timing to surgery, postoperative rehabilitation protocol, and other essential components of ACL reconstruction.

Introduction

Surgical treatment for anterior cruciate ligament (ACL) injuries was first reported in the early 20th century [1]. The first techniques focused on restoring anatomy and involved direct repair of the native ligament. Further knowledge of the contribution of the ACL towards rotatory knee stability led to attempts at extra-articular reconstruction using a combination of lateral tenodesis and posteromedial imbrication [2]. These techniques all produced poor overall outcomes, and focus was shifted towards reconstructing the native ACL. Early reconstruction techniques utilized an open arthrootomy [3]. Initial graft options included patellar tendon and fascia lata autograft with associate bone blocks, with hamstring and synthetic graft options explored over the next decade [4, 5]. Numerous graft fixation options were considered, including wires, extraarticular screws, suture tied over buttons, and interference screws [6]. Following the widespread adoption of knee arthroscopy, arthroscopic ACL reconstruction quickly gained popularity in the 1990s.

Initial arthroscopic reconstructions utilized transtibial drilling of the femoral tunnel [3]. Around this time, many surgeons focused on isometric graft placement [7], which subsequently fell out of favour amidst knowledge that the ACL is not an isometric structure [8,9]. Extensive research on graft placement confirmed the high prevalence of non-anatomic tunnel position with the traditional transtibial technique by the late 1990s [10], findings which persisted with the continued use of...
more modern transtibial drilling techniques [11]. Moreover, non-anatomic ACL reconstruction was shown to have an increased risk of anteroposterior (AP) and rotatory knee instability [12], poor patient-reported outcomes [13], revision [14], and post-traumatic osteoarthritis [15], prompting further investigation of anatomic reconstruction techniques.

Anatomic ACL reconstruction aims to restore the individual patient’s anatomy. This involves the recognition of anatomic patterns across all patients—including ACL footprint location—and differences among individual patients. There is appreciable variability in ACL footprint size, ACL width and notch morphology across patients (Fig. 1) [16]. By adapting surgery to the individual anatomy of the patient, the surgeon creates an appropriately sized and positioned graft for superior restoration of knee kinematics and improved clinical outcomes [17]. The goal of this review is to provide an overview of the relevant anatomy, preoperative planning and surgical techniques for anatomic ACL reconstruction, as well as to highlight the evidence supporting the advantages of anatomic reconstruction over conventional techniques.

**ACL anatomy**

Precise knowledge of the native anatomy of the ACL is crucial when performing anatomic ACL reconstruction. Embryologic studies have demonstrated the double-bundle structure of the ACL [18,19], consisting of anteromedial (AM) and posterolateral (PL) bundles, which function synergistically to provide AP and rotatory knee stability [20].

The ACL varies in length, ranging between 27 and 38 mm [21–23]. Originating from the medial aspect of the lateral femoral condyle, the ACL inserts lateral and anterior to the medial intercondylar spine of the tibia [24,25]. The femoral attachment of the ACL is located, on average, at 29% of the posterior-to-anterior distance along the lateral femoral condyle, and 35% of the superior-to-inferior distance [26]. The femoral and tibial footprints of the ACL show considerable variability among individuals, with cross-sectional areas of 60–130 mm² and 100–160 mm², respectively [21,27–30]. On the femur, the lateral intercondylar ridge, also referred to as the “resident’s ridge,” is located anterior to the attachment of the AM and PL bundles and is intersected perpendicularly by the lateral bifurcate ridge, which separates the two bundles [24]. On the tibia, the most relevant bony landmark is the medial tibial spine, with the centre of the tibial footprint located 6 mm anterior to the level of the apex of the medial tibial spine [31]. Differences in tibial footprint shape exist among individuals and are categorized as elliptical, triangular or C-shaped (in order of prevalence) [32].

Awareness of the cross-sectional area of the native ACL at the isthmus and insertion sites is important when determining the size of the ACL graft and fixation angle during reconstruction [22,27]. The smallest length and largest cross-sectional area of the ACL at the isthmus are both measured at 90° of flexion, highlighting the dynamic nature of the ligament throughout knee range of motion [32]. In addition, recent in vivo comparison of ACL morphometry between sexes has demonstrated a larger absolute volume of the ACL in men (1712.2 ± 356.3 mm³) compared to women (1200.1 ± 337.8 mm³), which may affect the assessment of injury risk and graft choice during anatomic ACL reconstruction [33].

**Preoperative considerations**

Initial preoperative assessment in anatomic ACL reconstruction includes a detailed history with a focus on age, sport and level of competition. Physical examination of both knees should be performed, noting side-to-side differences in alignment, range of motion (including hyperextension) and unilateral laxity suggesting ligamentous injury. The pivot shift test should be performed on both knees, as high-grade rotatory knee laxity may warrant additional stabilization procedures.

Surgical considerations and graft selection should be made in accordance with the patient’s functional demands, with younger patients and competitive athletes benefiting from an autograft with proven low retear rates in that population [34]. While objective examination is necessary, it is important to consider the individual patient's anatomy and functional demands when deciding on the optimal graft type. Preoperative planning and surgical techniques for anatomic ACL reconstruction should be tailored to each individual patient, taking into account the specific anatomy and functional demands.

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**Fig. 1.** Intraoperative measurements demonstrating elliptical (A) and triangular (B) ACL tibial insertion site shape variants.

**Fig. 2.** Preoperative MRI measurements of patellar and quadriceps tendon thickness (yellow), patellar tendon length (oblique blue), and patellar thickness (horizontal blue).
critical in initial diagnosis, physical characteristics including weight and height have not been shown to reliably predict ACL anatomic parameters, including the tibial insertion site [35]. There is evidence that graft size correlates with patient height and gender, with taller patients and males having significantly larger hamstring autograft diameter [36,37].

Biomechanical studies demonstrate that variations in coronal and sagittal plane alignment increase the forces exerted on the native and reconstructed ACL [38–40]. Both an increased posterior tibial slope and varus malalignment have been shown to increase the failure rates after ACL reconstruction [41,42]. Full limb length AP and lateral weight bearing radiographs should be obtained preoperatively for individuals with evidence of malalignment and can be used to assess the relative risk of failure of an isolated ACL reconstruction and plan for a concomitant corrective osteotomy.

In addition to radiographs, MRI is a standard component of the preoperative assessment. Midsagittal and midcoronal T1 MRI sequences can be used to measure the size of the tibial footprint, ACL length, inclination angle and thickness of potential autograft donor sites including the patellar, quadriceps and hamstring tendons (Fig. 2) [43–45]. Additional oblique coronal and sagittal sequences assist in identifying partial or single-bundle ACL injuries (Fig. 3) [46,47]. Ultrasound imaging presents a potential cost-effective alternative to MRI sequencing and has been verified as an accurate modality for assessing autograft size (Fig. 4) [48]. Intercondylar notch diameter is another anatomic feature that can be

Fig. 3. Oblique MRI sequences of a partial ACL injury. (A) Sagittal oblique image demonstrating an intact anteromedial (AM) bundle (white arrow) and torn posterolateral (PL) bundle (red arrow). (B) Coronal oblique image demonstrating haemorrhage in PL bundle (white arrow). (C) Coronal oblique image demonstrating intact AM bundle (white arrow). ACL, anterior cruciate ligament.

Fig. 4. Preoperative ultrasound evaluation of (A) the integrity of the ACL in the setting of injury, (B) graft sizing of the quadriceps tendon, and (C) graft sizing of the hamstring tendons (semitendinosus pictured). ACL, anterior cruciate ligament.
assessed on T1 MRI sequences during preoperative assessment. A small intercondylar notch size can present an additional challenge for ACL reconstruction, potentially impeding visualization and increasing risk of graft impingement. Anticipating a small notch can aid appropriate graft selection, anatomic femoral tunnel placement and overall operative efficiency [49].

Restoring the dimensions of the native ACL is a main principle of anatomic ACL reconstruction. A target restoration of 50–80% of the native tibial insertion site has been proposed in order to match the cross-sectional area of the graft to the average mid-substance size of the native ACL [22]. ACL graft options include patellar tendon, quadriceps tendon (QT) and hamstring tendon autografts, as well as allograft. Preoperative measurement of the tibial insertion site and the dimensions of available graft options are used to determine whether a single bundle reconstruction, in the case of a smaller footprint, or double bundle reconstruction, in the case of a larger footprint, is most appropriate. Performing ACL reconstruction with a graft that is too small increases the risk of rotatory knee instability and graft failure, whereas an oversized graft can lead to graft impingement in the notch and decreased range of motion [22,32]. Alternative techniques utilizing oblique dilators to produce oval bone tunnels have been proposed as a means of achieving greater footprint coverage and producing a “double-bundle-like” effect [50].

The ideal timing for performing ACL reconstruction remains a controversial and evolving aspect of treatment. Historically, delayed reconstruction was favoured in the majority of cases, allowing for a reduction in swelling, inflammation and preoperative physical therapy to improve range of motion and quadriiceps strength [51,52]. Conversely, a systematic analysis demonstrated no relationship between surgical timing and overall objective and subjective outcomes following ACL reconstruction [53]. There is now substantial evidence that prolonged instability associated with ACL insufficiency leads to cumulative intra-articular injury, with greater rates of meniscus and articular cartilage injury observed in the setting of delayed reconstruction [54,55]. With the combined benefits of restoring knee function and maximizing joint preservation, early anatomic ACL reconstruction with a goal of restoring preoperative range of motion is the most appropriate treatment for the young and active patient.

**Surgical technique**

**Examination under anaesthesia**

The patient is placed supine on the operative table. Bilateral lower extremities are examined and compared, assessing range of motion, Lachman test, anterior and posterior drawer, pivot shift test, varus and valgus stress at full knee extension and 30° of flexion and dial test at 30° and 90° of flexion.

**Surgical approach**

A two (or three-)portal technique can be utilized, including a high anterolateral portal (ALP) for visualization and an anteromedial portal (AMP) for femoral tunnel drilling per surgeon preference. The high ALP allows for excellent top-down visualization of the tibial footprint. If the femoral footprint is not well visualized through the ALP, then a central trans-patellar tendon portal may be established, giving a better view of the lateral wall of the notch [56]. An alternative third portal, the accessory AMP, may be used for femoral drilling if the AMP is too central, though this is often not needed with optimal positioning of the AMP under spinal needle localization. After a thorough diagnostic arthroscopy, attention is turned to the ACL remnant. The remnant ACL fibres are debrided with an arthroscopic shaver, with care to preserve the tibial and femoral insertion site fibres for identification of the footprints. Using a flexible ruler, the tibial footprint and intercondylar notch width are measured to individualize the size and type of the graft. Graft harvest proceeds in accordance with these findings, as well as preoperative assessment of the patient’s functional demands.

Attention is turned to tunnel placement. Accurate tunnels are critical for successful anatomic ACL reconstruction, as this ensures appropriate graft positioning and restoration of normal knee kinematics [3]. Adequate visualization is paramount to ensure anatomic placement of the femoral and tibial tunnels. The most reliable anatomic landmark is the remnant ACL stump. However, particularly in chronic cases, the ACL stump is absent, and bony landmarks should be utilized. On the femoral side, the lateral intercondylar and bifurcate ridges are reliable landmarks, with the femoral footprint positioned posterior to the lateral intercondylar ridge. Importantly, the lateral intercondylar ridge may manifest more as a slope change than a true ridge. The surgeon must be certain that they see the true posterior margin of the condyle and not mistake the lateral intercondylar ridge for the posterior margin. The most common error is overly anterior placement of the femoral tunnel, so care is taken to place it posteriorly on the condyle [57]. On the tibial side, the tibial spine, intermeniscal ligament and anterior horn of the lateral meniscus are landmarks for tibial tunnel placement [24,31,58]. The centre of the tibial footprint is located at the level of the posterior border of the anterior horn of the lateral meniscus, 6 mm anterior to the level of the apex of the medial tibial spine and 9 mm posterior to the intermeniscal ligament [24]. Alternatively, biplanar fluoroscopy can be utilized intraoperatively for tunnel placement, although this increases surgical time [59–61]. On a perfect lateral knee X-ray, the “Quadrant Method” is used with Blumensaat’s line as the superior margin of the rectangle and the edges of the lateral femoral condyle defining the other margins (Fig. 5). Three lines are drawn vertically and horizontally to create the grid. The anatomic femoral footprint of the ACL is located very near to 25% from the superior margin and 25% from the posterior margin of the grid [61].

The femoral tunnel is drilled first and can be performed through the AMP with the knee hyperflexed to 120° or with an outside-in technique, depending on surgeon preference. The tibial tunnel is drilled with a standard tibial aiming guide inserted through the AMP.

Numerous fixation devices are available, which can broadly be categorized as aperture fixation (interference screws) and suspensory fixation. The isolated or combined use of these methods may be employed for the fixation of both soft tissue and bone block grafts. Similarly, there is no standard protocol for graft preconditioning or tensioning. The senior author prefers to perform single bundle fixation with the knee in near-full extension with a posterior drawer force. In double bundle reconstruction, the PL bundle is secured first in knee full extension, followed by AM bundle fixation with the knee in 30–40 degrees of flexion.

**Postoperative protocol**

Immediately following the procedure, the patient is placed in a postoperative hinged knee brace, which is removed upon the return of a quadriiceps set. The patient may begin weight bearing as tolerated with two crutches for the first 2 weeks, as well as immediate knee range of motion exercises of the knee. The patient undergoes a customized rehabilitation protocol with a physical therapist starting in the first postoperative week, which is adjusted if concomitant procedures were performed (e.g. meniscal repair or articular cartilage procedures).

**Outcomes**

Comparisons between anatomic and non-anatomic ACL reconstruction techniques have been limited by the challenges of concretely defining “anatomic” reconstruction. While independent tunnel drilling (rather than transtibial) has improved the accuracy of tunnel placement, independent drilling alone does not guarantee an anatomic reconstruction. The Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist has been validated as a scale for evaluating the completeness of anatomic reconstruction techniques, with high inter-rater reliability, consisting of 17 items with a maximum score of 19 points (Table 1) [62]. A minimum score of 8 on the Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist indicates successful anatomic reconstruction.
Reconstruction Scoring Checklist has been utilized by several studies as the threshold for anatomic ACL reconstruction [15, 63, 64]. Randomized control studies comparing anatomic ACL reconstruction with traditional techniques have demonstrated that anatomic reconstruction results in decreased AP translation and reduced rotatory knee instability on pivot shift testing [65]. Furthermore, there is a significant decrease in rotatory knee instability in anatomic ACL reconstruction compared with non-anatomic reconstruction, with overall comparable failure rates and subjective outcomes between the groups [64]. However, a significantly greater proportion of traumatic graft failure has been found in the anatomic group, whereas non-anatomic reconstruction results in higher rates of atraumatic graft ruptures. The increased traumatic failures in anatomic reconstructions is postulated to relate to greater in situ graft forces experienced by the ACL after anatomic reconstruction [66]. Anatomic ACL reconstruction has also been shown to result in decreased rates of osteoarthritis, with a recent systematic review finding significantly lower rates of osteoarthritis after anatomic reconstruction (23%) compared to non-anatomic ACL reconstruction (44%) at over 15 year average follow-up [15].

Multiple randomized controlled trials and systematic reviews have compared outcomes between single and double bundle ACL reconstructions [67-74]. Double bundle reconstruction has demonstrated improved knee stability on anterior tibial translation, Lachman testing, and pivot shift testing, but has not shown a significant difference in patient-reported outcomes or failure rates. A prospective study assigning patents to either single or double bundle reconstruction based on pre-operative measurement of the ACL insertion site length (with a cutoff of 16 mm) found no difference in anterior tibial translation, rotary knee instability, and subjective outcomes, suggesting that successful outcomes can be achieved regardless of graft configuration when the principles of anatomic ACL reconstruction are followed [12].

Amidst the several available graft options for anatomic ACL reconstruction, large-scale national registry studies comparing surgical outcomes between graft types have not produced a clear consensus regarding the superiority of one particular autograft over others [75-80]. The majority of registry studies comparing HT and bone-patellar tendon-bone (B TB) autografts have reported a higher relative risk of revision in the HT group [75, 77, 81]. In a Norwegian population of high-level athletes competing in handball, soccer and alpine skiing, the risk of graft revision was 2.8 times higher in individuals younger than 18 years undergoing ACL reconstruction with HT than BTB autograft [82]. Studies from the Swedish National Knee Ligament Registry identified that diminishing HT graft diameter in 0.5 mm increments increases the risk of revision surgery [83], and HT graft diameters smaller than 8 mm have significantly a greater risk of failure than those 8 mm and larger [79].

The use of QT autograft has been increasing in recent years [84-88] and demonstrates comparable or superior functional outcomes relative to HT autograft [89]. The activity- and age-dependent rate of ipsilateral graft rupture has been demonstrated to be lower in patients with QT autograft compared to HT autograft ACL reconstruction [90]. However, a study from the Danish Knee Ligament Reconstruction Registry (DKLRR) identified a higher 2-year revision rate after ACL reconstructions using QT grafts compared to HT and BTB grafts [76]. Importantly, the inferior outcomes reported in the DKLRR following QT autograft were found to be concentrated at a small number of lower-volume centres, with high-volume centres having equivalent revision rates between graft types [91]. Further large-scale studies are needed to clarify the impact of graft choice on objective and functional outcomes following anatomic ACL reconstruction.

While surgical volume and skill are likely to have a strong impact on clinical outcomes after ACL reconstruction, there is currently a paucity of studies investigating the role of surgeon experience in the operative treatment of ACL tears. A recent study comparing the performance of high- (>35 per year) and low-volume (<35 per year) ACL surgeons in anatomic tunnel placement identified a higher rate of non-anatomic tunnel placement in the low-volume group, highlighting the importance of surgeon experience in ACL reconstruction [92].

**Future directions**

While ACL reconstruction has been investigated extensively, with over 20,000 publications on record, there remain unanswered questions, including within anatomic ACL reconstruction [93]. More large data, long-term, high-quality outcomes studies are needed to determine what techniques and grafts produce the best outcomes, and in which patient...
populations. Tailoring technique to individual patients is a pillar of anatomic ACL reconstruction. Studies must clarify the specific population under investigation and avoid grouping heterogeneous patients together. Multicentre and registry studies have the benefit of immense power, and though their overall populations are heterogeneous, they allow a large enough sample size to analyse specific patient groups with sufficient power. Given the abundance of new developments in ACL reconstruction over the past 40 years, there is no doubt that techniques and concepts will continue to evolve. 

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The authors dedicate this manuscript to the life and work of Dr. Freddie H. Fu. Dr. Fu was a pioneer in the world of sports medicine, nowhere more so than within anatomic ACL reconstruction. His research and vision have shaped the field, bringing anatomic ACL reconstruction into the mainstream and setting the stage for years of research to come. Dr. Fu’s legacy lives on in the countless surgeons, students, and providers that has taught and inspired over the decades. In the words of Dr. Fu, “thank you, thank you, thank you!"


