Anatomic anterior cruciate ligament reconstruction

Anatomska rekonstrukcija prednjeg križnog ligamenta

Garth N. Walker[1*], Jennifer D'Auria[2], Liang R. Cui[1], Carola F. Van Eck[1], Freddie H. Fu[1]

[1]Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania, USA

[2]Emory School of Medicine, Atlanta, USA

Received: 10.09.2014
Accepted: 20.01.2015

Abstract. Tears of the anterior cruciate ligament (ACL) are one of the most common injuries to active individuals. The history of reconstructing a ruptured ACL has undergone many advances from open, extra-articular reconstructions, to modern day advanced arthroscopic techniques. Some of these new arthroscopic techniques use small incisions and standardized instruments reducing the surgical time, however, they fail to restore the native ACL anatomy. Recent studies have shown that non-anatomical reconstruction might result in suboptimal clinical outcomes. As a result, anatomic ACL reconstruction has gained popularity. The cornerstone of anatomic ACL reconstruction is the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites. This article is meant to provide the most up-to-date literature review regarding anatomic ACL reconstruction.

Key words: anterior cruciate ligament; reconstruction

Sažetak. Ozljede prednjeg križnog ligament (PKL) spadaju među najčešće sportske ozljede koljena. Povijest rekonstrukcije PKL-a prešla je dug put od otvorenih metoda do današnji modernih artroskopskih tehnika. Pri nekim artroskopskim tehnikama koriste se male incizije uz upotrebu standardiziranih instrumenata, čime se značajno skraćuje vrijeme operacije, ali se ne uspijeva u cijelosti rekonstruirati anatomsko hvatište PKL-a. Novije studije pokazale su da se takvim rekonstrukcijama ne uspijevaju postići zadovoljavajući klinički rezultati. Cilj anatomske rekonstrukcije jest rekonstukcija prirodne duljine i promjera PKL-a, orijetnacije kolagenih vlakana i anatomskih hvatišta. U ovom radu dajemo pregled najnovije literature koja se bavi anatomskom rekonstrukcijom PKL-a.

Ključne riječi: prednji križni ligament; rekonstrukcija

***Corresponding author:**
Freddie H. Fu, MD, DSc
Department of Orthopaedic Surgery,
University of Pittsburgh Medical Center
Kaufman Building Suite 1011,
3471 Fifth Avenue,
Pittsburgh PA 15213, USA
e-mail: ffu@upmc.edu

http://hrcak.srce.hr/medicina

HISTORY OF THE ACL RECONSTRUCTION

The anterior cruciate ligament (ACL) is one of the most common ligaments injured by active individuals involved in cutting and pivoting sports. In the United States, the incidence of ACL injury have risen from 32.5 per 100,000 in 1994 to 43.5 per 100,000 in 2006, with the greatest increases seen in women and patients younger than 20 and older than 40 years old[1]. Historically, the ACL has been of great interest to orthopaedic surgeons and researchers alike. The first attempts at restoring the function of the ACL were in the early 1900s with direct primary repair; however, studies in the 1950s indicated that repair was associated with poor clinical outcomes. Increasing attention to ACL reconstruction in the 1970s transitioned focus to extra-articular reconstruction with lateral based procedures using the fascia lata often combined with limited intra-articular reconstructions[2]. During the 1980s and 1990s, the focus shifted from an extra-articular approach to an intra-articular technique. Insall described techniques where the anterior distal part of the iliotibial band with an attached bone block from Gerdy's tubercle was used as an intra-articular graft fixed by a screw to the tibia to control anterior instability. All of the aforementioned approaches required open surgery with large cosmetically-unappealing scars and long surgical recovery times.

From the MRI, preparation to individualize the surgery can be achieved by measuring the ACL insertion site size, ACL length, ACL angle, as well as the quadriceps and patellar tendon size for graft possibilities.

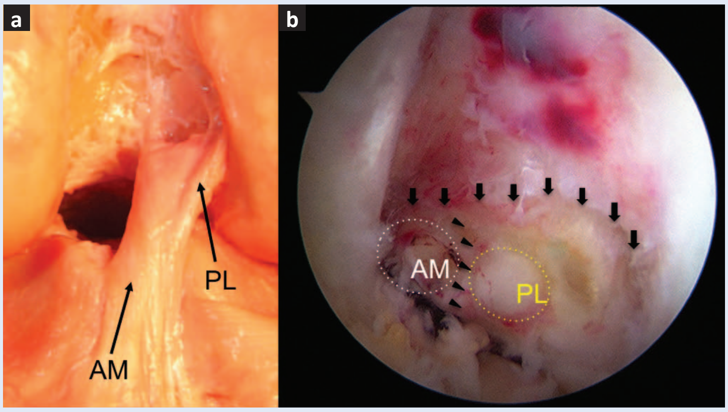

Figure 1. The anterior cruciate ligament (ACL): a) The ACL is composed of two distinct bundles: the anteriomedial (AM) and the posterolateral (PL) bundles; b) The AM and PL origins on the lateral femoral condyle showing the lateral intercondylar ridge (arrows) marking the superior border of the ACL origin and the lateral bifurcate ridge (arrowheads) forming the border between the AM and PL bundles.

In the 1980s, technology for arthroscopy had advanced such that it became a useful tool for ACL reconstruction beyond a routine visual aid. With arthroscopy, similar outcomes could be achieved without creating cosmetically-unappealing scars or having large surgical times seen in open surgery[3]. However, as surgeons became familiar with this new surgical technique, they often struggled to visualize the anatomy since the view was more limited without an open technique. Ultimately, new standardized instruments were developed to facilitate tunnel and graft placement obviating the need for direct visualization. These advancements did decrease surgical time and increased efficiency, but they fell short of anatomically reconstructing the ACL[3].

During the 2000s several biomechanical articles were published that demonstrated the then current ACL reconstruction techniques were unable to establish rotational kinematics. Tashman et al. demonstrated this in a study with 6 patients involved in downhill running at 4 and 12 months after transtibial single-bundle ACL reconstruction. Between the reconstructed knee and contralateral leg, patients had similar anteroposterior translation but significantly different rotational stability[4]. With this in mind, anatomic ACL reconstruction was developed with its focus being the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites[5]. This is expected to better restore native knee kinematics with the goal of reducing the rate of early osteoarthritis[4,6-8]. This review will address the most relevant issues related to anatomic ACL reconstruction.

ANATOMY OF THE ACL

The ACL is composed of two bundles: anteromedial (AM) and posterolateral (PL) bundles. Each bundle originates on the medial portion of the lateral femoral condyle posterior to the resident's ridge[9] (Figure 1). The resident's ridge was de-

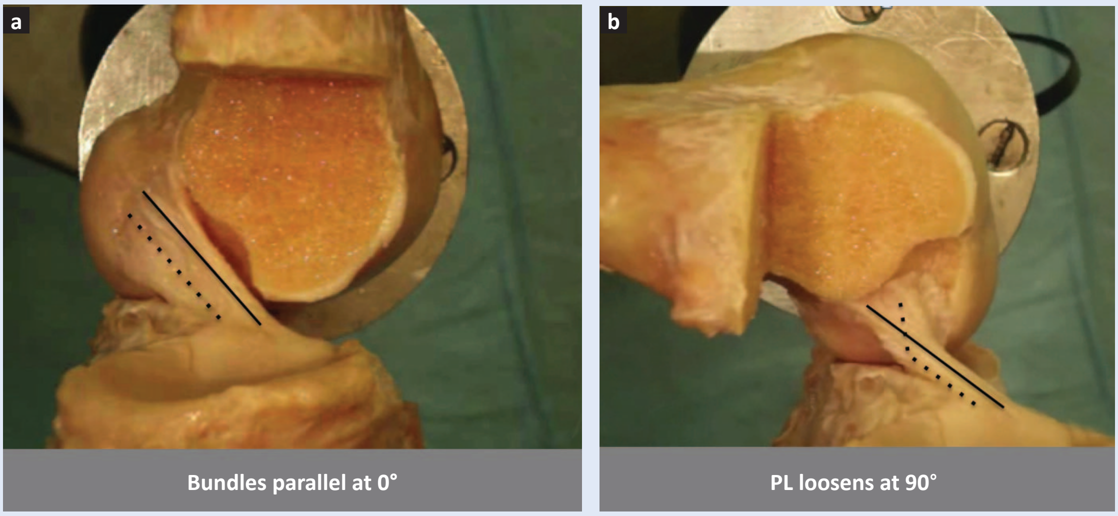

Figure 2. Orientation of the bundles change throughout the arc of motion: a, b) Both the AM (solid line) and PL (dotted line) bundles are parallel at full extension but are oriented differently as the knee approaches 90 degrees of flexion with the PL becoming loose.

scribed by Hutchinson et al. as a distinctive change in slope of the femoral notch roof that occurs just anterior to the femoral attachment of the ACL[9]. The femoral insertion site or ACL origin is located at the posterior aspect of the medial wall of the lateral femoral condyle. Ferretti et al. conducted an anatomic study and concluded that the length of the femoral footprint of the ACL is 17.7 ± 1.2 mm and the width is 9.9 ± 0.8 mm. Further in their analysis they found the surface of the origin of the two bundles is not flat with variations in the slope of each origin. The femoral attachment of the AM bundle forms an angle with the PL bundle of 27.6 ± 8.8 degrees. The average length of the femoral AM bundle is 9.8 ± 0.8 mm, and the average length of the femoral PL bundle is 7.3 ± 0.5 mm. An important bony landmark referred to as the lateral intercondylar ridge defines the anterior border of the femoral origin of the ACL. The lateral bifurcate ridge, another important osseous landmark, delineates the AM and PL bundle insertion areas, with the AM bundle proximal and PL bundle distal to this landmark[10]. However, it should be pointed out that the orientation of the bundles changes throughout flexion and extension (Figure 2). Near full extension, the bundles are parallel but have different orientations as the knee approaches 90 degrees of flexion[11].

In its midportion, the ACL tapers to a thinner diameter, similar to an hourglass shape. The cross-sectional area of the insertion sites are 3 to 3.5 times larger than the cross-sectional area of the ligament's midsubstance[12]. The ACL fibers fans out and insert on the center of the tibial plateau between the tibial spines consistent with their two given names of anteromedial and posterolateral. The length of the tibial insertion site and its area has been described with tremendous variability. Variability of the insertion site has been studied by Kopf et al. noting a range of 9-25 mm with the majority of patients between 14-18 mm[13,14]. The visualization of the AM and PL bundles is distinct in fetal studies. From the embryological stage, fetal anatomical and histological studies demonstrate two bundles with a septum between them[15].

INJURY PATTERN

ACL rupture occurs most frequently during athletic activity that entails high frequency actions of pivoting and cutting. The most common activities include soccer, basketball, lacrosse and football. During the mechanism of injury the patient is most likely to hear or feel a pop, most commonly non-contact and secondary to a planted foot that is hyperextended accompanied with valgus force. Afflicting females more often.

The most common modality used to reconstruct the ACL is arthroscopy. Arthroscopy allows for visualization and probing to delineate the rupture

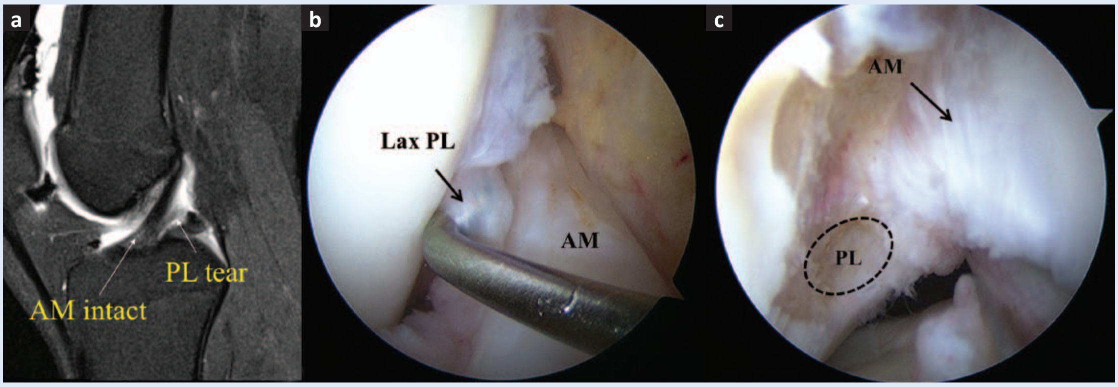

Figure 3. a) Sagittal MRI with increased signal in the PL bundle consistent with rupture while the AM bundle appears intact; b) The right knee viewed from the central portal shows injured PL and intact AM bundle; c) The AM bundle is being tested for integrity using a probe.

pattern. In some cases, a tear of a single bundle is found instead of a full two-bundle rupture allowing the surgeon to preserve the intact bundle. Another important notion of injury patterns is how different injury mechanisms can occur with the AM and PL bundles at varying strains that manifest in different rupture patterns. Two distinct injury mechanisms of ACL have been classically described by Muller et al.[16]: (1) hyperextension trauma, with resultant stretch of the ACL over the anterior intercondylar notch roof; and (2) moderate extension trauma, during which the AM bundle is taut and a valgus and/or external rotation force is applied. Based on the variable tension patterns exhibited at different positions of knee flexion, we have seen a variety of two bundle injury patterns and isolated AM or isolated PL bundle injuries. Isolated PL bundle injury occurs when stress is applied at or near full extension (Figure 3). In greater degrees of flexion (30 to 60 degrees), isolated AM bundle injury can occur.

Detailed dissection of the remnant ACL is an important first step prior to proceeding with the reconstructive portion of ACL surgery due to the prevalence of partial tears to the ACL during injury. Zantop et al. studied 121 consecutive patients and found that 25 % of patients had partial tears, with 12 % having no injury to the PL bundle. The other 75 % had complete tears of both bundles[17].

HISTORY AND PHYSICAL EXAM

For every patient, it is important for the provider to obtain a detailed history and physical exam to evaluate for an ACL rupture. Inquiry of the mechanism of injury and setting provides information on the correct differential diagnosis. Additionally, it is important to distinguish between acute and chronic injury. Acute injury will often present with a traditional presentation, while chronic injury may present with secondary injuries such as recurrent instability or giving way associated with sports or daily activity that may have great variability in presentation.

Evaluating the active and passive range of motion is important as well since it provides information on loose bodies, meniscal injuries or ACL impingement. The four most important physical exams and tests are Lachman test, pivot shift, anterior drawer test, and KT 2000 (Figure 4). The Lachman test, shown to be the most sensitive[18], involves positioning the knee at 30 degrees and evaluating for anterior translation. The pivot shift test is the most specific test and should be done with caution since the exam can be extremely uncomfortable for the patient. Because of this, guarding should be recorded to ensure that the results have not been confounded with pain. A more honest exam can be done when the patient is under general anesthesia where guarding can be blunted. The anterior drawer test is performed by laying the patient supine on the table with the hip flexed at 45 degrees and the knee to 90 degrees. The examiner positions himself by sitting on the exam table in front of the pathologic knee and grasping the tibia just below the joint line of the knee. The index finger is used to

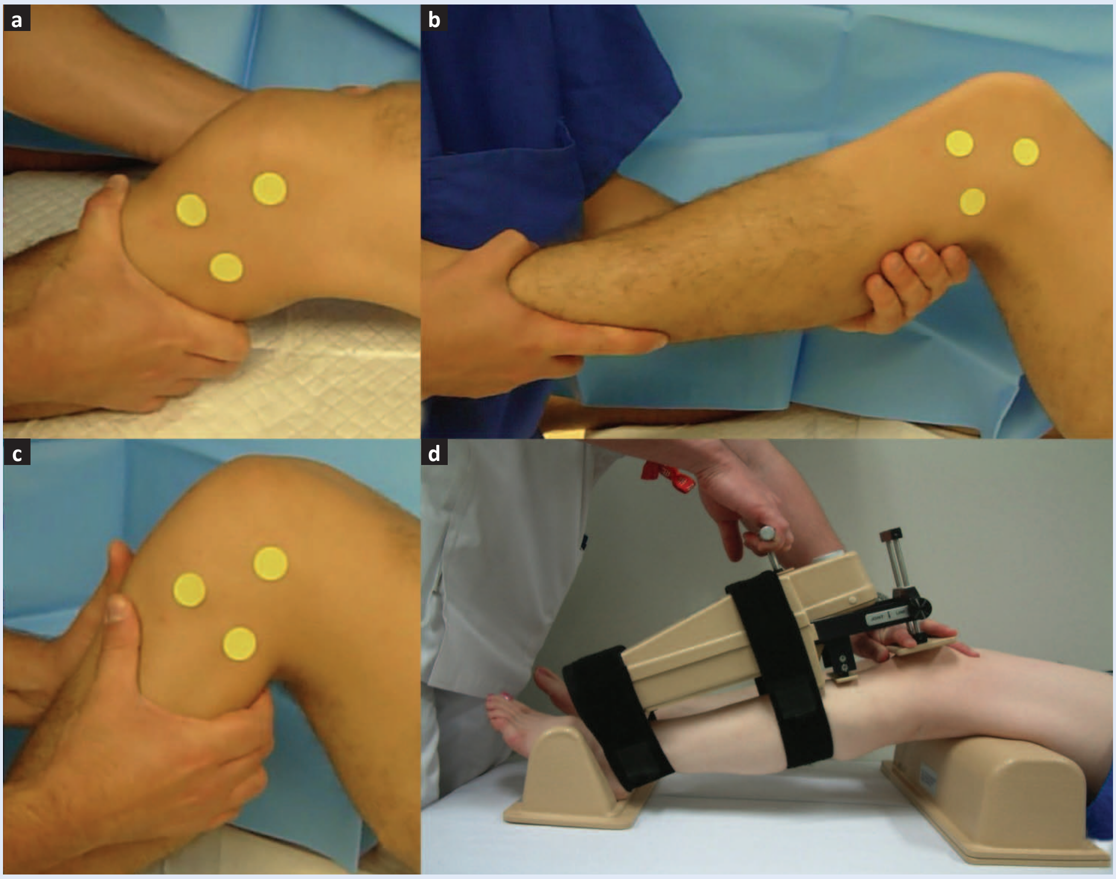

Figure 4. The four most important physical exams and tests for evaluating the active and passive range of motion. a) Lachman test; b) Pivot Shift test; c) Anterior Drawer test; d) KT 2000.

palpate hamstring muscles to ensure they are relaxed. The tibia is then pulled forward anteriorly and compared to the contralateral leg. An increased amount of translation without a firm endpoint indicates potential ACL tear. The KT 2000 is a device that can quantify the amount of looseness from anterior to posterior of the knee as well as the tightness. An additional utility is that the KT 2000 allows the comparison of the unhealthy knee to the contralateral healthy knee.

PERTINENT IMAGING AND PRE-OPERATIVE CONSIDERATIONS

Preoperatively the physician should obtain standing AP and lateral X-rays to ensure fractures did not occur during the mechanism of injury. The most important imaging modality for anatomic ACL is the MRI which allows both functional bundles to be viewed specifically through sagittal, sagittal oblique, and coronal oblique imaging (Figure 5). The special imaging allows for optimal visualization of both bundles demonstrated by Starman et al.[19]. From the MRI, preparation to individualize the surgery can be achieved by measuring the ACL insertion site size, ACL length, ACL angle, as well as the quadriceps and patellar tendon size for graft possibilities (Figure 6). Because each patient's anatomy is different and varies on a spectrum (Table 1), these measurements allow the physician to predict the appropriate intraoperative decisions best suited for an anatomically placed ACL as well as an estimate for the appropriate graft size[20,21]. These measurements are then confirmed intra-

Because each patient's anatomy is different and varies on a spectrum these measurements allow the physician to predict the appropriate intraoperative decisions best suited for an anatomically placed ACL as well as an estimate for the appropriate graft size. These measurements are then confirmed intra-operatively.

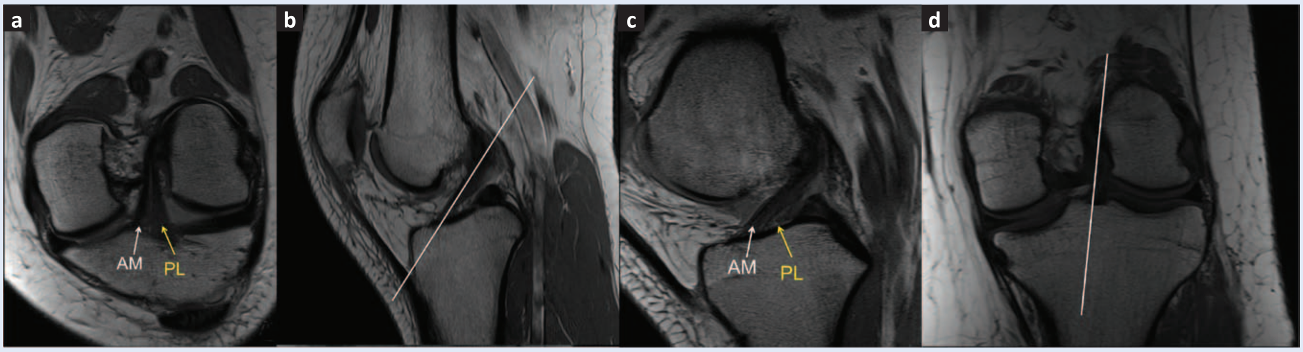

Figure 5. Specialized MRI views along the plane of the ACL can be used for optimal visualization of the two functional ACL Bundles. a) A coronal oblique MRI showing the AM and PL bundles in an intact ACL; b) Scout line views of the coronal oblique view projected onto a sagittal MRI; c) Sagittal oblique MRI of the same knee showing both AM and PL bundles in the same ACL as a); d) Scout line views of the sagittal oblique view projected onto a coronal MRI.

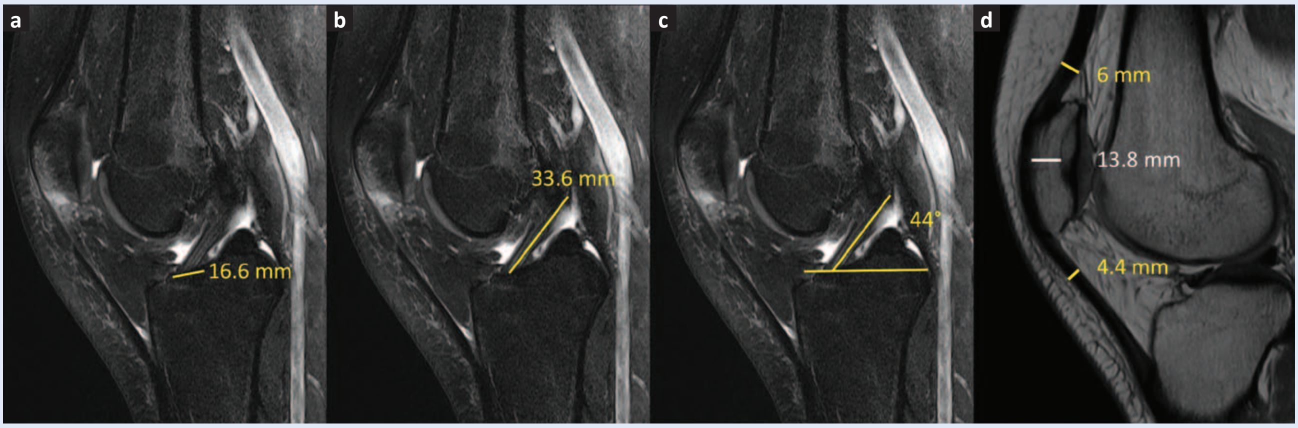

Figure 6. Pre-operative measurements are performed on a sagittal MRI. Measurements obtained include: A) the tibial insertion site length of the ACL; B) length of the ACL; C) ACL inclination angle; D) thicknesses of the quadriceps and patellar tendons as well as the patella.

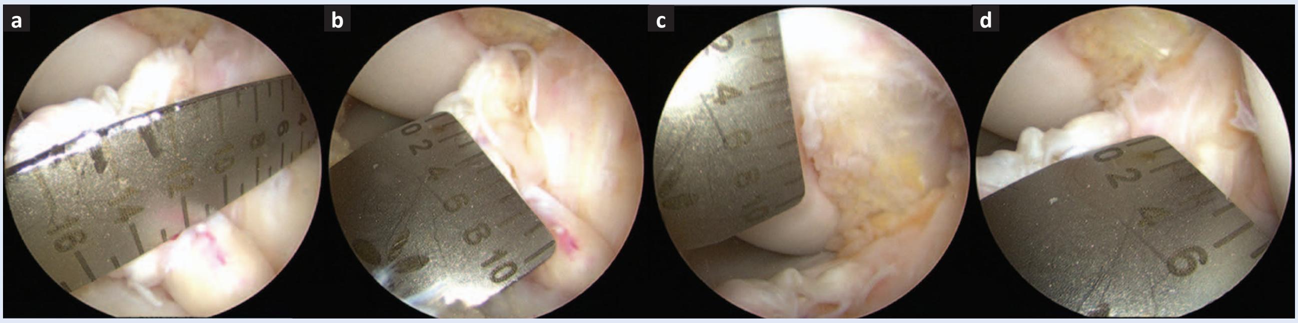

Figure 7. Intraoperative measurements are taken to objectively assess individual anatomy. Native tibial insertion site length (a) and width (b) provides information used to dictate the technique used for ACL reconstruction. Notch height (c) and width (d) provides information about how much room there is for surgery to be performed without risk of iatrogenic injury or impingement affecting graft function.

Table 1. Frequency of tibial insertion site lengths and corresponding indications for single bundle (SB) versus double bundle (DB) ACL reconstruction. This is a bimodal distribution at 16 and 18 mm.

Frequency of Tibial Insertion Site Lengths (%)					
12-13 mm	14-15 mm	16 mm	17 mm	18 mm	19-22 mm
3.6	13.9	20.4	11.7	34.3	16.1
< 14 mm: SB	14-18 mm: SB or DB			> 18 mm: DB	

Table 2. Advantages and disadvantages of available graft choices for ACL reconstruction

Graft Choice	Advantages	Disadvantages
Hamstring	• Comparable strength to native ACL • Ease of harvest • Minimal donor site morbidity • Cosmesis of donor site	• Graft size can be unpredictable • Soft-tissue healing • Not suitable for patients or athletes who rely heavily on hamstring muscles
Bone-patellar tendon-bone (BPTB)	• Bone-to-bone healing in femoral and tibial tunnels • Comparable stiffness to native ACL	• Not suitable for double-bundle ACL reconstruction • Weaker than native ACL • Fixed length • Invasive, large incision • Risk of patellar fracture • Risk of anterior kneeling pain
Quadriceps tendon	• Large graft and versatile: could be used for single or double-bundle reconstruction • Option of a one-sided bone block	• Less stiffness than native ACL • Large, invasive incision • Risk of patellar fracture
Allograft	• No donor size morbidity • Versatile and available in various types and sizes	• Longer healing time • Increased risk of re-rupture, especially in younger patients and irradiated grafts • Theoretical risk of disease transmission

operatively (Figure 7). If a patient is undergoing revision surgery, several visualizing modalities can prepare the physician before surgery. Specifically, MRI and 3D CT scan are particularly useful for looking at previously drilled tunnels to help guide tunnel placement in revision cases[22].

Preoperative planning also includes proper graft choice. Each choice can aid in individualizing the approach. The types of grafts used include hamstring, quadriceps, bone-patellar-tendon-bone (BPTB), and allograft (Figure 8) (Table 2).

The hamstring graft may be recommended for the patient who desires an aesthetic outcome. Hamstring grafts acts in similar strength to the ACL but some of the downfalls are less controllable size and residual weakness in the hamstrings. The quadriceps tendon can be used for SB or DB reconstruction along with bone incorporation, but can be too bulky and places the patient at risk for patella fracture. The allograft provides the most flexibility since there is no donor site morbidity, but the risk of re-rupture is high, there is a longer healing time, and there is a theoretical complication of host rejection[23]. Lastly, for large insertion sites and anatomy, grafts can be pooled together to increase the diameter to meet the size (Figure 9 and Table 3).

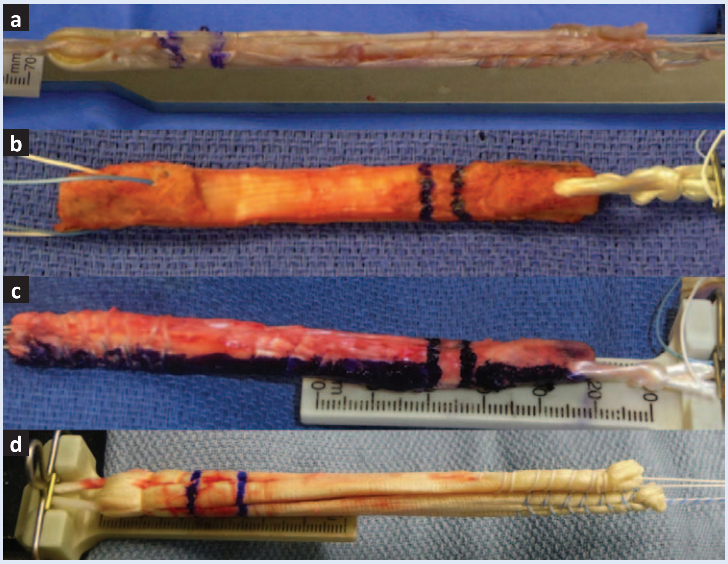

Figure 8. A wide variety of grafts may be used for ACL reconstruction including: a) hamstring autograft; b) bone-patellar tendon-bone autograft; c) quadriceps tendon autograft with bone block; d) allograft which is depicted here as a double bundle.

Anatomic ACL reconstruction was developed with its focus being the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites.

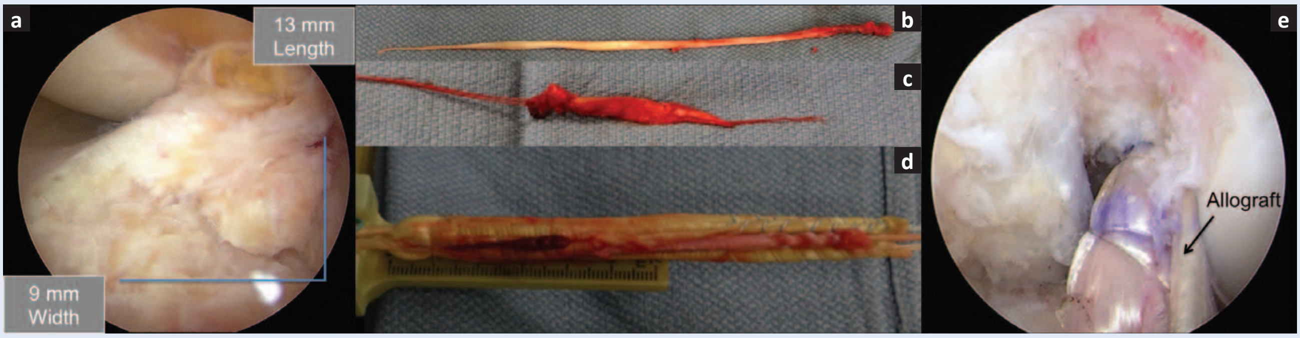

Figure 9. An example of supplement allograft to an insufficient autograft. The native tibial insertion site area was measured with a ruler intra-operatively and found to be 13 mm in length and 9 mm in width (a). Harvest of hamstring autograft was performed but the semitendinosus was 2.5 mm in diameter and 5 mm in a double loop (b) and the gracilis was unusable (c). The native tibial insertion site area was calculated using the formula of an ellipse and it was found that using a 5mm hamstring graft, only 26 % of the insertion site area would be restored. An option is to supplement the harvested autograft with allograft. This patient received a hybrid semitendinosus allograft (9 mm diameter) (d-e) This percentage reconstructed area was increased to 84 % using this method.

Table 3. Percentage reconstruction of this patient's tibial insertion site varying with graft diameter. With and without allograft augmentation are shown in underline and bold, respectively.

Graft Diameter (mm)	Percentage Reconstructed Area of Tibial Insertion Site
4	17
<u>5</u>	<u>26</u>
6	38
7	51
8	68
9	**84**

NON-OPERATIVE AND OPERATIVE TREATMENT

Non-operative treatment might be the best option for patients with the following characteristics: incomplete tears, no symptoms of instability, no involvement in high-demand sports, open growth plates, or sedentary lifestyles[25]. For individuals choosing non-operative management, treatment is still necessary and includes ambulatory assistance with crutches until full weight-bearing is tolerated, icing to reduce swelling, and early involvement in physical therapy. This rehabilitation protocol is not unlike that for post-ACL reconstruction and involves approximately 6 months of exercises that not only strengthen the muscles around the knee but also train the body to react in a way that puts less strain on the knee. Even for young active adults, non-operative treatment might be a viable option as shown in a randomized controlled trial that compared rehabilitation and early surgical intervention to rehabilitation and optional delayed surgery[26]. With a study population of 121 young active adults, there were no significant differences in KOOS (Knee Injury and Osteoarthritis Outcome Score), 36-Item Short Form Health Survey, Tegner Activity Scale, or osteoarthritis index at 5 year follow-up[26]. However, it should be noted that 51 % of the patients in the delayed group opted for operative intervention eventually[26]. The incidence of meniscal pathology was also higher in the patient group treated without surgery.

If operative management is selected, it is recommended that ACL reconstruction be delayed until swelling diminishes, normal range of motion is regained, and near normal gait and strength is established[27]. A delay between injury and ACL reconstruction has also been supported when there is a quadriceps strength deficit of more than 20 %. This has been associated with significant post-operative strength decreases[28]. In addition, there is significantly less arthrofibrosis is seen when reconstruction is delayed by three weeks[29].

The decision for single- or double-bundle reconstruction should be based on patient preference, patient level of activity, and on intra-operative measurements (size of ACL at its mid-portion, ACL insertion sites, and intercondylar notch width)[30]. The contraindications for double bundle reconstruction are the same as the indications for single bundle reconstruction. These include ACL insertion site less than 14 mm, notch width less than 12

Table 4. Contraindications for double-bundle ACL Reconstruction

- Total tibial insertion site length < 14 mm is indication for single bundle technique.
- Single-bundle tear is indication for augmentation technique when intact bundle remains functional
- Relative Contraindications
- Open physes
- Severe bone bruising
- Narrow notch (notch width < 14 mm)
- Shallow notch (notch height < 14 mm)
- Severe arthritic changes (grade 3 or greater)

Open physes and severe bone bruising would likely benefit from less iatrogenic damage through less tunnel drilling. A narrow and shallow notch does not easily accommodate two bundles, is technically demanding for anatomic tunnel placement, and may lead to graft impingement resulting in early graft failure. Lastly, severe arthritic changes may worsen more rapidly when the knee is constrained with two bundles.

mm, open physes, severe bone bruising, cartilage greater than grade 3, and multiligament injuries[5] (Table 4).

A three-portal approach using lateral, central medial, and accessory medial portals provides maximal visualization of the ACL and its femoral and tibial insertion sites as well as providing instrument portals for optimal tunnel drilling[31] (Figure 10). Insertion sites can be identified by not only ACL remnants but also anatomic landmarks. The anterior horn of the lateral meniscus and the medial and lateral horns of tibial spines are aligned with the tibial insertion site while the lateral intercondylar and bifurcate ridges demarcate the femoral insertion site[32]. The bony landmarks are very important for chronic cases when the footprints cannot be visualized specifically[5]. During double-bundle reconstruction, the tunnels for the posterolateral and anteromedial bundles are placed in the center of the native AM and PL bundle insertion site in such a way as to maximize coverage of the native femoral and tibial insertion site[33] (Figure 11).

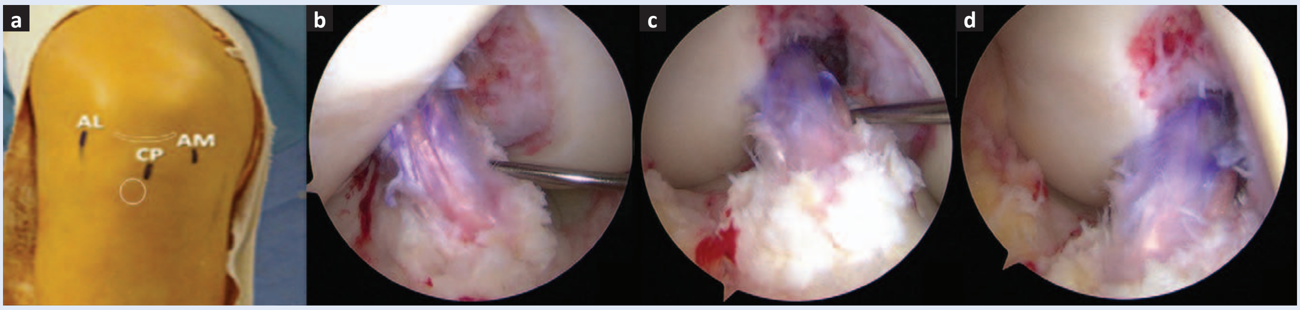

Figure 10. a) The three portal technique provides the best visualization of the ACL insertion sites. First a high accessory lateral (AL) portal is created. Then, under arthroscopic visualization using a spinal needle, the central portal (CP) and accessory medial (AM) portals are created. b-d) arthroscopic views of through the AM, CP, and AL portals, respectively.

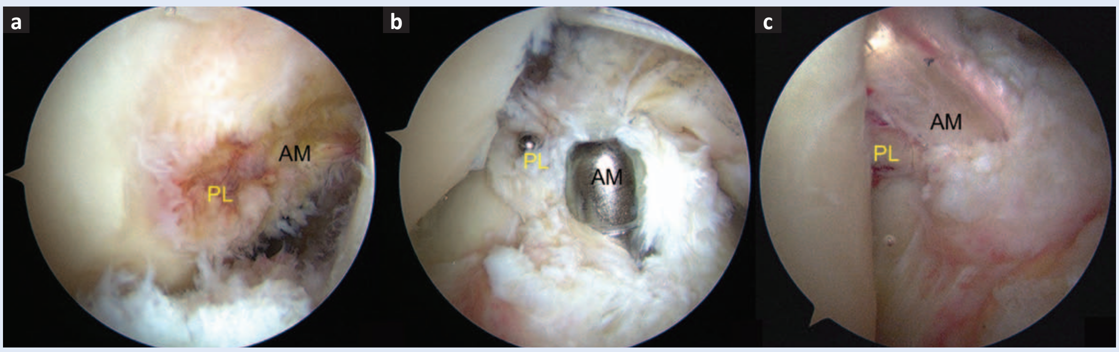

Figure 11. a) Anatomic locations of the PL and AM femoral origins; b) Tibial AM and PL bundles; c) Double bundle reconstruction with graft in place.

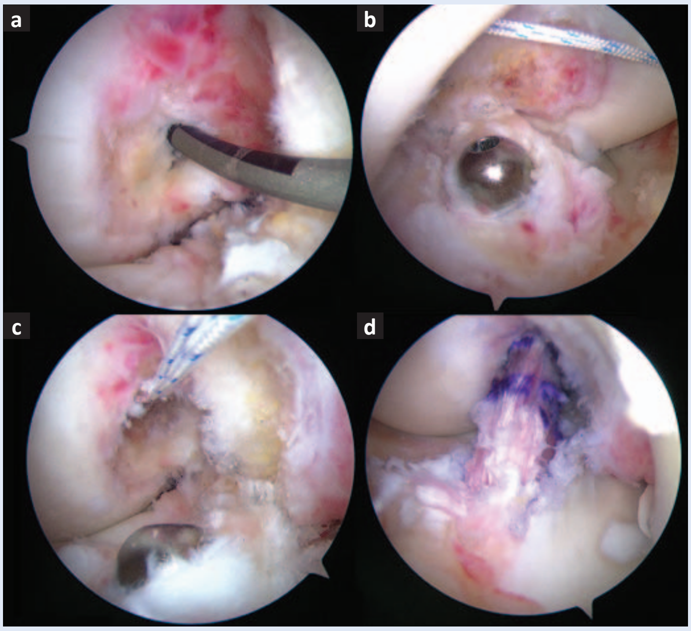

Figure 12. a) Arthroscopic view of drilled single femoral tunnel; b) Tibial Tunnel placement; c) View of both the femoral and tibial tunnels; d) Graft in place

Anatomic SB reconstruction has great overlap to anatomic DB reconstruction. However, instead of drilling a separate tunnel for the AM and PL bundle, one tunnel is placed in the center of the ACL insertion site on both the femoral and tibial side (Figure 12). Measurements of the notch size, tibial and femoral insertion site are documented to corroborate pre-operative measurements taken on MRI.

BIOMECHANICS

In vivo biomechanical studies have demonstrated the importance of each bundle's value to encourage repair of the ACL deficient knee. Kopf et al evaluated the function of the AM and PL bundle intra-operatively with the use of a computer navigating system. Fifteen patients with acute ACL ruptures underwent anatomic ACL reconstruction. The patients were divided into groups and compared accordingly: ACL deficient to PL bundle reconstructed knee, ACL deficient to DB ACL reconstructed knee, and PL bundle reconstructed knee to DB ACL reconstructed knee. Each patient was examined preoperatively, after fixation of the PL bundle individually, and then after fixation of the PL and AM bundles together. A computer navigation system tracked the kinematics for Lachman test, anterior drawer test, internal-external rotation at 30 degrees of knee flexion, and varus-valgus rotation at 30 degrees of knee flexion. Fixation of the PL bundle improved knee laxity on Lachman and anterior drawer test, but additional fixation of the AM bundle improved results even further[35].

Biomechanical analyses involving cadaveric specimens suggest that anatomic reconstruction is superior to non-anatomic reconstruction. In a cadaveric study comparing ACL reconstruction using double bundles placed anatomically to a single bundle re-approximating only the anteromedial bundle, the anatomic double bundle technique was found to be superior in reproducing the in situ forces and rotatory loads seen in ACL intact knees[6]. More specifically, ACLs reconstructed with the anatomic double bundle technique relative to intact ACLs saw 97 % of anterior tibial loads and 91 % of rotatory loads; whereas ACL knees reconstructed with the anteromedial single bundle technique only saw 89 % of anterior tibial loads and 66 % of rotatory loads[6]. Another cadaveric study compared anatomic double bundle and anatomic single bundle reconstruction to knees with intact and deficient ACLs[36]. The intact states could not be recreated with either the anatomic double or single bundle reconstruction as there were significant differences when comparing the reconstructed states to the intact state for anterior tibial loads, simulated pivot shift, external and internal rotations, and valgus and varus rotations at various flexion angles[36]. All but external rotation which showed a small significant difference, no significant differences were found between the anatomic double and anatomic single bundle reconstructions[36]. Thus, the study by Yagi et al. shows the biomechanic superiority of the anatomic double bundle reconstruction, and the study by Goldsmith et al. suggests that while ACL reconstruction cannot recreate the intact state, double and single bundle reconstructions can have similar biomechanical outcomes if reconstructed anatomically.

REHABILITATION PROTOCOL

While anatomic ACL reconstruction may allow for faster achievement of normal range of motion, rehabilitation needs to be carried out with the knowledge that grafts placed anatomically experience greater in situ forces than grafts placed non-anatomically[37]. While this might indicate the need for a slower rehabilitation protocol, previous studies have shown no differences in accelerated and non-accelerated programs. In the randomized controlled trial carried out by Beynnon et al. no differences between accelerated (19 weeks) and non-accelerated (32 weeks) programs existed in clinical assessment, functional performance, proprioception, thigh muscle strength, increase in knee laxity, and lack of return of KOOS (Knee Injury and Osteoarthritis Outcome Score) and quality of life to pre-injury levels[38].

In the early post-operative period, goals and milestones of therapy include: control of pain and edema, graft protection, comparable extension of involved and uninvolved knees, knee flexion of at least 100 degrees, maintenance of quadriceps strength, and achievement of full weight-bearing and normal gait[39]. Typically this period spans the first 6 weeks post-operatively. Crutches with instructions to weight bear as tolerated help to protect the graft and to minimize pain. Excluding cases of concomitant meniscal injury and repair, bracing after ACL reconstruction is not indicated as many randomized controlled trials have not seen benefit in pain reduction, range of motion, graft stability, or rate of re-injury[40,41]. Similarly, no clear benefit is seen with the use of the CPM machine[39]. Conversely, cryotherapy improves outcomes by reducing pain and swelling[39,41].

After the early post-operative period, rehabilitation should be geared at strengthening and neuromuscular control before progression of returning to activity and sports. These phases are cautiously given the time frames of 9-16 weeks and 16-22 weeks[41], respectively; however, achievement of certain criteria should serve as the benchmarks for progression. During the strengthening and neuromuscular control stage, patients should perform activities of daily living without difficulty, tolerate exercises testing flexion and strength without pain or edema, and jog 2 miles if attainable pre-injury[39]. While this will be discussed further, returning to activity and sport should not be allowed unless patients attain a quadriceps index of at least 85 % and can handle sprinting, cutting, pivoting, jumping, and hopping at full exertion[39].

RETURN TO SPORT

Return to sport after ACL reconstruction has been researched in the past, but specific return to sport for patients that have undergone anatomic ACL reconstruction is relatively sparse. Van Eck et al. evaluated failures and predictors of anatomic ACL reconstruction and noted younger age, BMI, and early return to sport (222 vs 267 days) as the strongest predictor of failure[42]. Part of this may be due to the tendency of the anatomic ACL to experience the natural forces of the knee that a non-anatomically placed ACL can withstand[43].

Most protocols for anatomic ACL reconstruction have been grouped into the general description of return to play after ACL surgery. These guidelines tend to be vaguely defined with no set agreement on the appropriate time to engage in activity. The decision to return to play also rests on the patient's subjective view of their readiness. A study by Tjong et al. evaluated qualitatively the decision to return to play with the prime focus on understanding what factors influence decision to return to pre-injury level status after ACL reconstruction. They interviewed 31 patients who had participated in sports before ACL rupture and had them complete Marx activity score logs and questionnaires focused on level of play. For patients that refused to play with good knee function their apprehension fit into three overarching themes: fear, lifestyle changes, and innate personality traits[44].

ACL injury following return to play can be dependent on gender, side of injury, and graft choice. A prospective study evaluated 100 soccer athletes, 55 males and 45 female, with an average follow-up of 7 years about when they returned to play, current status, and reason for stopping athletic activity. 72 % initially returned to play after surgery, and 36 % were still playing 7 years later. Twelve patients sustained injury with 9 injuring their contralateral leg. The study concluded that male athletes were more likely to return to play and have less chance of re-injury compared to females. Additionally older athletes were less likely to return to sport, and injury to the non-dominant leg places the dominant leg at future risk of injury[45]. Return to play research has primarily been focused on general ACL reconstruction without particular focus on anatomic reconstruction; thus, more research is needed to ascertain the effect of anatomical ACL reconstruction on return to play.

CLINICAL OUTCOMES AFTER ANATOMIC ACL RECONSTRUCTION

Comparison of anatomic and double bundle and single bundle reconstruction has been documented in literature, but the need for more prospective and randomized control trials still exist. A prospective and randomized study involving 281 patients compared ACL reconstruction using anatomic double bundle, anatomic single bundle, and non-anatomic single bundle techniques[46]. Statistically significant differences were found between the groups with anterior tibial translation of 1.2 mm, 1.6 mm, and 2 mm for anatomic double bundle, anatomic single bundle, and non-anatomic single bundle techniques, respectively[46]. This study suggests that anatomic double bundle reconstruction was superior to anatomic and non-anatomic single bundle reconstructions[46]. Pivot shift supported the superiority of double bundle and anatomic reconstruction in that the percentage of patients who had scores of 0 for pivot shift were 93.1 % for anatomic double bundle, 66.7 % for anatomic single bundle, and 41.7 % for non-anatomic single bundle[46]. There were no differences in subjective IKDC scores between the groups.

OSTEOARTHRITIS AFTER ANATOMIC ACL RECONSTRUCTION

ACL injury in general poses a substantial risk for early onset osteoarthritis (OA) especially in the setting of concomitant meniscal injury[47-49]. Li et al. evaluated the prevalence and risk factors for the development of radiographic knee OA after transtibial single bundle ACL reconstruction. In this study, 249 individuals were classified by the Kellgren-Lawrence (KL) scale into degree of OA in the medial, lateral, and patellofemoral compartments. Patients were included on the basis of comparison to the contralateral healthy knee: if the difference was at least 2 grades in 1 compartment or 1 grade in 2 compartments, patients were included. Thirty-nine percent had radiographic OA at 7.8 years after surgery. Meniscal damage, or previous meniscal surgery, female gender, BMI, chondrosis of patellofemoral and medial compartment, and length of follow-up were correlated for early OA radiographic findings. Despite good outcomes and return to sport, early onset of OA after ACL reconstruction was still prevalent with the strongest predictors related to obesity, and grade 2 or greater chondrosis in the medial compartment[50].

The evaluation of anatomically reconstructed knees on cartilage status has not been examined specifically, but recent research has posed a potential protective value of anatomically placed ACLs. In a study by Chu et al, they used quantitative magnetic resonance imaging with ultra short echo-time pulse sequencing (UTE T2) to evaluate changes of the deep cartilage matrix in anatomically placed ACL knees as a measure to detect early cartilage damage over 2 years. 35 patients undergoing ACL reconstruction were given an Outerbridge cartilage grade of 0-4 at time of surgery and compared to 11 uninjured controls. After 2 years, 16 of the patients underwent UTE-T2 of the deep central and posterior medial femoral condyle and medial tibial plateau. Results demonstrated decreased levels of UTE T2 to levels of the uninjured knee, suggesting a potential protective value[51]. More studies are needed to compare anatomically reconstructed knees to non-anatomically reconstructed knees.

WHAT IS IN STORE FOR THE FUTURE

Reconstructing the ACL should maximally re-approximate native anatomy as anatomic reconstruction appears to be superior from both a biomechanical and clinical standpoint to non-anatomic reconstruction. However, comparisons between anatomic double and anatomic single bundle reconstruction are less clear. Biomechanically, double bundle reconstruction appears to be superior showing less anterior translation and better ability to reproduce the forces seen by the ACL in the intact state. Clinically, though, meta-analysis has shown little significant difference in outcome scores. Lastly, rehabilitation protocol specific to anatomic ACL reconstruction should be of future interest to optimize outcomes following surgery. As anatomic double and single bundle ACL reconstructions have only become common in practice over the past decade, studies showing long-term follow up that examine the likelihood of delayed outcomes such as osteoarthritis are minimal to date. Thus, the decision to proceed with double or single bundle reconstruction should be individualized to respect a patient's particular knee anatomy.

Conflicts of interest statement: The authors report no conflicts of interest.

REFERENCES

1. Mall NA, Chalmers PN, Moric M, Tanaka MJ, Cole BJ, Bach BR Jr et al. Incidence and Trends of Anterior Cruciate Ligament Reconstruction in the United States. Am J Sports Med 2014;42:2363-70.
2. McCulloch PC, Lattermann C, Boland AL, Bach BR Jr. An illustrated history of anterior cruciate ligament surgery. J Knee Surg 2007;20:95-104.
3. Harner CD, Irrgang JJ, Paul J, Dearwater S, Fu FH. Loss of motion after anterior cruciate ligament reconstruction. Am J Sports Med 1992;20:499-506.
4. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 2004;32:975-83.
5. van Eck CF, Lesniak BP, Schreiber VM, Fu FH. Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. Arthroscopy 2010;26:258-68.
6. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL. Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. The American journal of sports medicine 2002;30:660-6.
7. Fu FH, Shen W, Starman JS, Okeke N, Irrgang JJ. Primary anatomic double-bundle anterior cruciate ligament reconstruction: a preliminary 2-year prospective study. Am J Sports Med 2008;36:1263-74.
8. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH. Individualized anterior cruciate ligament surgery: a prospective study comparing anatomic single- and double-bundle reconstruction. Am J Sports Med 2012;40: 1781-8.
9. Hutchinson MR, Ash SA. Resident's ridge: assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. Arthroscopy 2003;19:931-5.
10. Ferretti M, Ekdahl M, Shen W, Fu FH. Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthroscopy 2007; 23:1218-25.
11. Wang JH, Kato Y, Ingham SJ, Maeyama A, Linde-Rosen M, Smolinski P et al. Measurement of the end-to-end distances between the femoral and tibial insertion sites of the anterior cruciate ligament during knee flexion and with rotational torque. Arthroscopy 2012;28:1524-32.
12. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL. Quantitative analysis of human cruciate ligament insertions. Arthroscopy 1999;15:741-9.
13. Kopf S, Pombo MW, Szczodry M, Irrgang JJ, Fu FH. Size variability of the human anterior cruciate ligament insertion sites. Am J Sports Med 2011;39:108-13.
14. Kopf S, Musahl V, Tashman S, Szczodry M, Shen W, Fu FH. A systematic review of the femoral origin and tibial insertion morphology of the ACL. Knee Surg Sports Traumatol Arthrosc 2009;17:213-9.
15. Ferretti M, Levicoff EA, Macpherson TA, Moreland MS, Cohen M, Fu FH. The fetal anterior cruciate ligament: an anatomic and histologic study. Arthroscopy 2007;23:278-83.
16. Muller W. Form, Function, and Ligament Reconstruction. Berlin: Springer- Verlag 1982.
17. Zantop T, Brucker PU, Vidal A, Zelle BA, Fu FH. Intraarticular rupture pattern of the ACL. Clin Orthop Relat Res 2007;454:48-53.
18. Prins M. The Lachman test is the most sensitive and the pivot shift the most specific test for the diagnosis of ACL rupture. Aust J Physiother 2006;52:66.
19. Starman JS, Vanbeek C, Armfield DR, Sahasrabudhe A, Baker CL 3rd, Irrgang JJ et al. Assessment of normal ACL double bundle anatomy in standard viewing planes by magnetic resonance imaging. Knee Surg Sports Traumatol Arthrosc 2007;15:493-9.
20. Hofbauer M, Muller B, Murawski CD, van Eck CF, Fu FH. The concept of individualized anatomic anterior cruciate ligament (ACL) reconstruction. Knee Surg Sports Traumatol Arthrosc 2014;22:979-86.
21. Araujo P, van Eck CF, Torabi M, Fu FH. How to optimize the use of MRI in anatomic ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 2013;21:1495-501.
22. Basdekis G, Christel P, Anne F. Validation of the position of the femoral tunnels in anatomic double-bundle ACL reconstruction with 3-D CT scan. Knee Surg Sports Traumatol Arthrosc 2009;17:1089-94.
23. Murawski CD, van Eck CF, Irrgang JJ, Tashman S, Fu FH. Operative treatment of primary anterior cruciate ligament rupture in adults. J Bone Joint Surg Am 2014;96: 685-94.
24. Desai N, Bjornsson H, Musahl V, Bhandari M, Petzold M, Fu FH et al. Anatomic single- versus double-bundle ACL reconstruction: a meta-analysis. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2014;22:1009-23.
25. Buss DD, Min R, Skyhar M, Galinat B, Warren RF, Wickiewicz TL. Nonoperative treatment of acute anterior cruciate ligament injuries in a selected group of patients. Am J Sports Med 1995;23:160-5.
26. Frobell RB, Roos HP, Roos EM, Roemer FW, Ranstam J, Lohmander LS. Treatment for acute anterior cruciate ligament tear: five year outcome of randomised trial. BMJ 2013;346:f232.
27. Shelbourne KD, Patel DV. Timing of surgery in anterior cruciate ligament-injured knees. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 1995;3:148-56.

28. Eitzen I, Holm I, Risberg MA. Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. British journal of sports medicine 2009;43:371-6.
29. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. The American journal of sports medicine 1991;19:332-6.
30. Middleton KK, Hamilton T, Irrgang JJ, Karlsson J, Harner CD, Fu FH. Anatomic anterior cruciate ligament (ACL) reconstruction: a global perspective. Part 1. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2014;22:1467-82.
31. Cohen SB, Fu FH. Three-portal technique for anterior cruciate ligament reconstruction: use of a central medial portal. Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association 2007;23:325 e1-5.
32. Yasuda K, van Eck CF, Hoshino Y, Fu FH, Tashman S. Anatomic single- and double-bundle anterior cruciate ligament reconstruction, part 1: Basic science. The American journal of sports medicine 2011;39:1789-99.
33. Karlsson J, Irrgang JJ, van Eck CF, Samuelsson K, Mejia HA, Fu FH. Anatomic single- and double-bundle anterior cruciate ligament reconstruction, part 2: clinical application of surgical technique. The American journal of sports medicine 2011;39:2016-26.
34. Amis AA. The functions of the fibre bundles of the anterior cruciate ligament in anterior drawer, rotational laxity and the pivot shift. Knee Surg Sports Traumatol Arthrosc 2012;20:613-20.
35. Kopf S, Musahl V, Bignozzi S, Irrgang JJ, Zaffagnini S, Fu FH. In Vivo Kinematic Evaluation of Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction. Am J Sports Med 2014;42:2172-7.
36. Goldsmith MT, Jansson KS, Smith SD, Engebretsen L, LaPrade RF, Wijdicks CA. Biomechanical comparison of anatomic single- and double-bundle anterior cruciate ligament reconstructions: an in vitro study. The American journal of sports medicine 2013;41:1595-604.
37. Kato Y, Ingham SJ, Kramer S, Smolinski P, Saito A, Fu FH. Effect of tunnel position for anatomic single-bundle ACL reconstruction on knee biomechanics in a porcine model. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2010;18:2-10.
38. Beynnon BD, Johnson RJ, Naud S, Fleming BC, Abate JA, Brattbakk B et al. Accelerated versus nonaccelerated rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind investigation evaluating knee joint laxity using roentgen stereophotogrammetric analysis. The American journal of sports medicine 2011;39:2536-48.
39. Yabroudi MA, Irrgang JJ. Rehabilitation and return to play after anatomic anterior cruciate ligament reconstruction. Clinics in sports medicine 2013;32:165-75.
40. Wright RW, Fetzer GB. Bracing after ACL reconstruction: a systematic review. Clinical orthopaedics and related research 2007;455:162-8.
41. van Grinsven S, van Cingel RE, Holla CJ, van Loon CJ. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2010;18:1128-44.
42. van Eck CF, Schkrohowsky JG, Working ZM, Irrgang JJ, Fu FH. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. Am J Sports Med 2012;40:800-7.
43. Kato Y, Maeyama A, Lertwanich P, Wang JH, Ingham SJ, Kramer S et al. Biomechanical comparison of different graft positions for single-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2013;21:816-23.
44. Tjong VK, Murnaghan L, Nyhof-Young JM, Ogilvie-Harris DJ. A Qualitative Investigation of the Decision to Return to Sport After Anterior Cruciate Ligament Reconstruction To Play or Not to Play. American Journal of Sports Medicine 2014;42:336-42.
45. Brophy RH, Schmitz L, Wright RW, Dunn WR, Parker RD, Andrish JT et al. Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the Multicenter Orthopaedic Outcomes Network (MOON) group. Am J Sports Med 2012;40:2517-22.
46. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH. Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. The American journal of sports medicine 2012;40:512-20.
47. Badlani JT, Borrero C, Golla S, Harner CD, Irrgang JJ. The effects of meniscus injury on the development of knee osteoarthritis: data from the osteoarthritis initiative. Am J Sports Med 2013;41:1238-44.
48. Magnussen RA, Mansour AA, Carey JL, Spindler KP. Meniscus status at anterior cruciate ligament reconstruction associated with radiographic signs of osteoarthritis at 5- to 10-year follow-up: a systematic review. J Knee Surg 2009;22:347-57.
49. Kambic H. The meniscus--a key to unfolding the mystery of osteoarthritis: commentary on an article by Robert H. Brophy, MD, et al.: "Molecular analysis of age and sex-related gene expression in meniscal tears with and without a concomitant anterior cruciate ligament tear". J Bone Joint Surg Am 2012;94:e31.
50. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ. Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med 2011;39:2595-603.
51. Chu CR, Williams AA, West RV, Qian Y, Fu FH, Do BH. Quantitative Magnetic Resonance Imaging UTE-T2* Mapping of Cartilage and Meniscus Healing After Anatomic Anterior Cruciate Ligament Reconstruction. Am J Sports Med 2014;42:1847-56.