Management of Anterior Cruciate Ligament Injury
What's In and What's Out?

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Abstract

Sports medicine physicians have a keen clinical and research interest in the anterior cruciate ligament (ACL). The biomechanical, biologic, and clinical data researchers generate, help drive injury management and prevention practices globally. The current concepts in ACL injury and surgery are being shaped by technological advances, expansion in basic science research, resurging interest in ACL preservation, and expanding efforts regarding injury prevention. As new methods are being developed in this field, the primary goal of safely improving patient outcomes will be a unifying principle. With this review, we provide an overview of topics currently in controversy or debate, and we identify paradigm shifts in the understanding, management, and prevention of ACL tears.

Keywords: *Anatomy, anterior cruciate ligament, injury management, reconstruction, rehabilitation*
MeSH terms: *Anterior cruciate ligament, anterior cruciate ligament reconstruction, rehabilitation, recovery of function*

Introduction

The anterior cruciate ligament (ACL) is considered the primary passive restraint to anterior translation of the tibia on the femur, and it provides rotational stability to the knee in both the frontal and transverse planes.[1-3] ACL tears account for up to 64% of athletic knee injuries in cutting and pivoting sports, and these injuries result in 120,000–200,000 ACL reconstructions (ACLRs) performed annually in the United States alone, with a cost of around 1.7 billion US dollars annually.[4-7] Injuries to the ACL often result in joint effusion, altered knee kinematics and gait, muscle weakness, and reduced functional performance, and they are associated with long term clinical sequelae such as meniscal tears, chondral lesions, and development of early onset posttraumatic osteoarthritis (OA).[8-16] The ACL is among the most heavily studied anatomic structures in the human body, resulting in a plethora of biomechanical, biologic, and clinical data, driving paradigm shifts in nearly every facet of ACL injury management and prevention. In the following sections, we provide a brief overview of where ACL injury management has been, the driving forces for where it is today, and where it is going.

Anterior Cruciate Ligament Anatomy, Biomechanics, and Injury Mechanisms

The ACL is comprised of two bundles which are named for their relative insertion sites on the tibia: anteromedial (AM) and posterolateral (PL). Along the lateral wall of the intercondylar notch, two prominent osseous ridges mark the borders of the femoral ACL insertion site: the lateral intercondylar ridge demarcates the anterior border of the ACL, while the lateral bifurcate ridge, running perpendicular to the lateral intercondylar ridge, separates the femoral attachment sites of the two bundles.[14,17] The AM bundle is nearly isometric, with a tendency toward slightly more tension during flexion than in extension.[4] Due to this quality, the AM bundle is considered the center of ACL rotation.[18] The PL bundle is lax in flexion and becomes taught during the end range of extension (from 15° of flexion to 0°).[4] This relationship allows the AM bundle to provide both rotational and translational (sagittal plane) stability, whereas the PL bundle provides more rotational stability.[4]

In 2013, Iriuchishima *et al*. described that the ACL has a smaller cross-sectional area at its midsubstance in comparison to its tibial and femoral attachments.[19,20] Further,

How to cite this article: Raines BT, Naclerio E, Sherman SL. Management of anterior cruciate ligament injury. What's in and what's out?. Indian J Orthop 2017;51:563-75.

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Access this article online
Website: www.ijoonline.com
DOI: 10.4103/ortho.IJOrtho_245_17
Quick Response Code:

the ACL has a band-like shape along its length, fanning out like a trumpet at its tibial insertion site, and crescent-like shape at the femur.[21-23]

There are three main ACL injury mechanisms: direct contact, indirect contact, and noncontact.[24-26] Direct contact injuries are sustained when a person or object strikes the knee directly. Indirect contact injuries occur when a person or object strikes a part of the body other than the knee itself, causing excessive forces to be transferred through the knee (such as a direct blow the thigh, translating the femur posterior in respect to the tibia), resulting in ACL failure. Noncontact injuries are sustained when a deceleration or change in direction (pivot) force are applied to the knee but often encompass an ill-timed neuromuscular firing of structures around the knee, causing translation of the tibia on the femur, which results in ACL failure.[24-26] Noncontact mechanisms account for 60%–70% of ACL injuries. The neuromuscular and biomechanical factors which play into this mechanism will be discussed later during the injury prevention section.[24,25,27-30]

Treatment Options and Techniques

Nonoperative, repair, and reconstruction

Nonoperative management of ACL tears is poorly tolerated by both young active adults and in the skeletally immature. This often leads to recurrent instability and the development of chondral and meniscal injuries.[4,14-16] A 2016 Cochrane review looked at randomized control trial outcomes of adult patients undergoing nonoperative management of ACL ruptures in the form of structured rehabilitation alone versus ACLR followed by structured rehabilitation. One study identified by reviewers found no difference between surgery and conservative treatment in patient-reported knee scores at 2 and 5 years. However, 39% of the participants randomized to the nonoperative treatment group underwent either ACLR for continued knee instability or meniscus repair within 2 years of their ACL rupture, while 51% did so within 5 years.[31]

ACL repair was the first reported surgical treatment in the management of ACL tears, first described by Robson in the early 1900s, and it is performed by re-approximating the ruptured ends of the native ACL with the use of suture or suture anchors.[1,32] Conversely, ACLR is characterized by debriding the torn end of the native ACL, and a new ligament is reconstructed using grafts such as hamstring tendon (HT), bone-patellar tendon-bone (BPTB), or quadriceps tendon (QT) to reconstitute the anatomy and function of the native ACL.[1] This tissue can be harvested from the patient (autograft) or from a cadaver (allograft).

Reconstruction types: Nonanatomic, anatomic, single- and double-bundle techniques

Traditional ACLRs are considered nonanatomic, placing the graft outside of the native insertion of the ACL. Vertically oriented grafts, often observed in nonanatomic reconstructions, have demonstrated the ability to reconstitute stability in the sagittal plane (anterior-posterior) but fail to provide adequate rotational stability.[4] Further, nonanatomic tunnel placement can alter the forces experienced by the graft and is one of the main reasons grafts fail (continued instability or re-rupture) after ACLR.[14,33,34]

The current trend is toward anatomic ACLR in an attempt to restore the native ACL footprint on both the tibial and femoral sides of the knee to recreate the native functional kinematics.[4] A "one-size fits all" approach to ACLR is not recommended as variation in anatomy, injury pattern, and demands between individuals should influence the surgeon's decision-making. In general, decisions in ACLR types should be guided by the following principles:

1. Double bundle reconstruction surgery is, in general, considered in patients with a large tibial insertion site (anteroposterior length >14 mm), large intercondylar notch (length and width >14 mm), in the absence of concomitant ligament injuries, absence of advanced arthritic changes (Kellgren Lawrence grade <3), absence of severe bone bruising, and closed physes
2. Single bundle reconstruction, conversely, is indicated for tibial insertion sites less than 14 mm in length, narrow notches (less than 12 mm in width), in the presence of concomitant ligamentous injuries, severe bone bruising, severe arthritic changes (grade 3 or higher Kellgren Lawrence changes) and in the setting of open physes.[14,35-37]

The purpose of the double-bundle graft is to reconstruct both the AM and PL bundles, with the intent of more closely reproducing the native knee anatomy and subsequently kinematics.[17,19,38] Multiple biomechanical studies support this concept.[19,39-41] However, other studies present conflicting data and raise concerns. A 2012 Cochrane review assessed both subjective and objective clinical outcome data in double-bundle versus single-bundle ACLR in adults. Although there was limited evidence that double-bundle ACLR has some superior results in objective measurements (i.e., return to preinjury activity level, International Knee Documentation Committee [IKDC] knee examination, KT-1000 scores, and for rotational stability on pivot shift test); insufficient evidence was found to determine relative effectiveness (i.e., subjective knee scores, long term knee pain, complications).[42]

When patients are individually assigned to treatment groups based on the size of the ACL native insertion site and the intercondylar notch width, prospective studies demonstrate no difference in terms of anteroposterior and rotational laxity between single or double-bundle reconstruction techniques.[14,43] A number of studies demonstrate that the biomechanical promise of double-bundle reconstruction fails to translate into clinical significance and may predispose the graft to impingement and excessive tension through the PL bundle during knee extension, resulting early graft rupture or attenuation.[14,19,39-41,44] Further, other biomechanical studies demonstrate that anatomic single-bundle grafts tensioned either maximally in extension or submaximally at 20°–30° of flexion most closely reproduce native knee kinematics.[4] As such, double-bundle reconstruction has lost momentum in the United States in favor of anatomic single bundle reconstruction.[45-48]

Tunnel drilling

Tunnel drilling is a topic of paradigm shift as growing literature expresses concerns with difficulty in achieving anatomic reconstruction with transtibial drilling of femoral tunnels. As such, transtibial technique is falling more out of practice (decreased from 56.4% in 2007 to 17.6% in 2014) as a growing number of surgeons perform an outside-in technique or use guides placed through the AM portal (increased from 41.3% in 2007 to 65.1% in 2014).[49] Outcome data including fewer persistently positive Lachman and pivot shift tests, lower KT-1000 scores, and higher Lysholm scores in the transtibial groups further support this paradigm shift.[4,49,50]

Fixation types

At this time, there is no clear consensus on superiority of aperture, suspensory cortical, or button graft fixation or screw (metal/biologic) versus button graft fixation. There are multiple types of screw types available for the use in aperture fixation, broadly falling under metal versus biologic/bioabsorbable screws. Biologic screws can be associated with tunnel widening, a complication infrequently observed in metallic screw fixation. However, biologic screws allow for advanced imaging of the knee postoperatively without metal artifact. From 2007 to 2014, Tibor *et al*. report a decrease in use of first-generation bioabsorbable screws for graft fixation and a shift toward biocomposite fixation when performing interference screw fixation.[49] When securing soft tissue grafts, recent studies favor suspensory fixation which fosters better junctional bone-tendon healing as well as stronger zero time fixation.[4] These basic science studies have translated into a 12%–13% yearly increase (from 2007 to 2014) in the use of femoral-sided suspensory fixation for soft tissue grafts.[49]

Graft Type

The selection of a graft type should be based on patient-specific factors (i.e., patient age, skeletal maturity, and activity level) and supported by evidence in the current literature.[4,6] There are tradeoffs between autograft and allograft and within subsets of these two categories (i.e., HT, QT, and BPTB). The surgeon must be conscientious of donor side and site morbidity when taking autografts, as well as biomechanical properties of different graft types as they apply toward the demands of the patient, regardless of the graft type (HT, QT, and BPTB).

When considering autograft versus allograft, Wasserstein *et al*. demonstrate a 2.6-fold higher rate of failure when using allograft versus autograft in patients <25 years of age, concluding that autograft remains the graft of choice in young athletes aiming to return to high-level athletic activities.[4,51] Again, this highlights that use of allograft is not recommended in treating the young or high-demand patient.

The use of nonirradiated allograft has been increasing in the older and/or less active population. Nonirradiated allograft reconstruction has been associated with an increased risk of graft failure in young, active patients. However, when used in a middle-aged or recreational athlete, nonirradiated allograft reconstruction has demonstrated acceptable and often equivalent outcomes to autograft, provided that strict rehabilitation parameters are set to allow 8–12 months for graft ligamentization before return to recreational activities.[4,52]

Recent studies comparing BPTB and HT autografts demonstrate an increased risk of failure/revision ACLR, persistently positive pivot shift test, diminished return to preinjury levels of activity, and higher rates of infection associated with HT autograft, while BPTB autografts have a higher incidence of anterior knee pain and pain when kneeling.[4,53,54]

Allograft augmentation of autografts has become a topic of recent investigation. One recent study assessed the clinical and cost-effectiveness of hamstring autograft alone versus a hybrid of hamstring autograft with semitendinosus allograft augmentation in patients under 18 years of age. Jacobs *et al*. reported an 11.9% failure rate in those receiving the hybrid HT autograft with allograft augmentation versus 28.3% failure rate in those receiving HT autograft alone. This reduced revision rate also translated into an incremental cost savings of US$2765.[55]

Quadriceps autograft

Regarding graft choice, BPTB and hamstring autografts have long been considered the main graft choices for young, active patients. The advantages of the patella tendon graft include a strong stiff graft, secure fixation, potential for bone-to-bone ingrowth, and low failure rates. However, BPTB autografts can be associated with significant donor-site morbidity.[56,57] HT grafts have demonstrated equivalent functional outcomes and less donor-site morbidity than BPTB but with increased laxity and higher failure rates.[56] Because of this tradeoff, surgeons have continued to search for alternative graft options, leading to the increased popularity of QT autografts.[56,58] In clinical studies, QT grafts have demonstrated good strength, low donor-site morbidity, and reliable long term outcomes.[56,59] Historically, QT grafts have been used for ACL revision surgery but never gained general acceptance for primary ACLR. However, QT graft harvest and fixation techniques have been simplified using a minimally invasive approach and this makes it an increasingly attractive option for primary reconstruction.[60]

Fischer *et al*. explain that since the quadriceps is an ACL antagonist, slightly impaired function of this muscle may protect the ACL graft against the quadriceps anteriorly directed force, whereas decreased hamstring strength combined with high relative quadriceps strength may increase risk for ACL rupture.[61] Further, biomechanical studies demonstrate that the residual strength of the QT after graft harvest is higher than that of the intact patellar tendon, which suggests that extensor mechanism strength is compromised less by QT graft harvest than by BPTB.[57]

A number of clinical studies have found good outcomes and support the selection of QT as an option for graft choice. Systematic reviews conclude that QT autograft ACLR yields good outcomes and stability comparable to BPTB and HT grafts regarding postoperative Lachman's test, pivot-shift test, IKDC scores, and Lysholm scores, with minimal donor-site morbidity.[56,57] No differences in residual laxity or patient-reported outcomes have been described between BPTB and QT in primary ACLR, while QT autograft is associated with better outcomes regarding extensor mechanism strength with equal or better functional outcomes than HT graft, without affecting morbidity.[58] Patients who underwent primary ACLR with QT autograft demonstrate significantly higher hamstring-to-quadriceps ratio than HT grafts within 1 year after surgery, which may be protective during the first several months of ACL graft maturation.[61] A recent systematic review concludes that the use of QT for ACLR is safe, reproducible, and versatile.[58]

Resurgence of Primary Anterior Cruciate Ligament Repair

Historically, poor outcomes have been associated with primary ACL repair. Results reported by Feagin and Curl and Cabaud *et al.* led to the generalized preference of ACLR over repair.[4,62-66] However, a number of limitations affect the generalizability of these early results as follows.

1. Repair was attempted on all types of ACL tears
2. Many had concomitant ligamentous injuries
3. The inherent morbidity associated with open approaches and prolonged postoperative immobilization led to significant motion loss and patellofemoral issues.[67,68]

Recently, there has been an increasing interest in ACL preservation as an option to perhaps better restore native ACL anatomy, biomechanics, and neurosensory function.[65,69] The reason for this paradigm shift is due to advancements in magnetic resonance imaging (MRI) quality, regenerative medicine and tissue engineering capabilities, arthroscopic techniques and instrumentation, as well as a better appreciation of the importance of early mobilization in rehabilitation.[1,67,68,70]

Primary repair aims to preserve the native ACL's inherent healing capacity, proprioceptive function, and knee kinematics.[67-69,71-74] Histological analysis demonstrates that the proximal one-third of the ACL has an intrinsic healing response similar to the medial collateral ligament and that the proximal and distal remnants of a torn ACL are mechanoreceptor rich.[75] Primary ACL repair can now be performed arthroscopically with the use of newer devices, which allows the remnant to be tensioned directly, while advanced approaches to rehabilitation with a focus on early motion help mitigate the high rates of stiffness and debilitating patellofemoral pain seen in prior series.[65,76]

Achtnich *et al*. compared clinical and radiographic outcomes between primary ACL repair and reconstruction at a minimum 2-year followup.[70] They reported a 15% failure rate in the repair group versus 0% in the reconstruction group and confirmed ACL presence on MRI in 100% of reconstruction cases versus 86% of repairs at a mean followup of 28 months. However, they concluded that primary repair was a reasonable option in a select patient population and could restore stability and yield good functional outcomes comparable to that of reconstruction, a conclusion echoed by Taylor *et al*. in their 2015 systematic review.[70,77]

In general, primary ACL repair does not burn bridges in the event of revision; failed repair is treated similar to a primary ACLR. In contrast, failed reconstruction can be fraught with complex obstacles and complications such as tunnel widening, preexisting tunnel malposition, removal or management of interference screws, and the need for bone grafting.[65,76]

It is important to carefully select the correct patients for primary repair. Sherman *et al*. stressed the importance of assessing ACL tear type and tissue quality, noting that patients with proximal avulsion tears (Sherman Type 1: soft tissue avulsion directly off the femoral footprint with minimal residual ligament on the femur) and excellent tissue quality are the best patient subset to consider for primary repair.[1,65,66]

Overall, primary ACL repair may be considered in the setting of proximal tears with good tissue quality, whereas ACLR remains the preferred technique in nonproximal tears (Sherman Type 3, 4 or midsubstance), those with concomitant ligamentous injuries (limiting early ACL focused rehabilitation), or those with poor tissue quality.[1,66-68]

Internal Bracing

While ACLR, primary ACL repair, or partial bundle reconstruction are treatment options that can be performed in isolation, augmentation of these constructs with an internal brace is an evolving surgical option.[76] Internal bracing represents a promising area in novel ACL research. The goal is to help protect the graft during early rehabilitation and to facilitate safe and efficient return to activity with the potential for reduced re injury risk.[78] Use of collagen coated, ultrahigh molecular weight polyethylene/polyester suture tape as an internal brace has been investigated.[69] Clinical studies demonstrate improved stability and graft protection. Basic science studies have demonstrated that the internal brace functions as a load-sharing device, still allowing the graft to see enough stress to undergo ligamentization.[79]

Concerns remain regarding the safety of exposed intraarticular, collagen-coated, ultrahigh-molecular-weight polyethylene/polyester suture tape. However, in a canine study investigating ACLR with concomitant internal bracing, Cook *et al*. found that the combined tendon allograft with synthetic suture tape allowed for an effective biologic-synthetic hybrid load-sharing ACL construct, prevented early failure, allowed for direct, four-zone graft-to-bone healing, and functional graft remodeling while avoiding soft tissue reaction and other problems prominently associated with all-synthetic grafts without the development of premature OA.[79]

In clinical studies that look at ACL repair augmented by internal brace, included patients demonstrated functional stability with near-normal knee function, excellent patient satisfaction, and return to previous levels of competition activity in the majority of patients.[80] These findings are promising also helping to support the recent paradigm shift in the treatment of proximal ACL tears as previously discussed.

Anterolateral Ligament

In 2013, Claes *et al*. formally described the anterolateral ligament (ALL).[81] This study brought attention back to the extraarticular anterolateral soft tissue structures of the knee. There has been much debate about the function of the ALL and defining the role of surgical reconstruction in the setting of ACL tear.

The ALL is proposed to provide rotational stability to the knee and to a lesser extent anterior tibial translation. Imbert *et al*. describe more specifically that, in their biomechanical study, an anisometric behavior of the ALL is observed – where the ALL is tight in both extension and in the presence of internal rotation at 20° of flexion, and that the ligament relaxed through continued flexion to 120° and continued to be lax during internal rotation at 90° of flexion.[82] Isolated ACLR can fail to fully restore normal rotational stability, which may contribute to subsequent articular injuries.[83] Biomechanical studies demonstrate that in an ACL-deficient knee, the ALL experiences significantly increased forces during anterior drawer and Lachman's tests and to a lesser extent during pivot shift. Further, these studies have found 2–3 mm of increased anterior tibial translation after sectioning of the ALL.[84] Because of its potential role in preventing translation and internal rotation near extension, it may be a factor behind a high grade of pivot shift and a failure to restore normal kinematics in some individuals undergoing ACLR only; a majority of biomechanical, clinical, and cadaver studies support this theory.[82-86]

As noted above, there is still some disagreement regarding the role of individual anterolateral structures as well as the management of rotatory laxity in ACL-deficient knees. However, it is known that the anterolateral structures do significantly contribute to rotational knee stability. Surgical treatment should be considered in the setting of ACL injury with a high-grade pivot shift or persistent pivot shift following anatomic reconstruction, in young active patients with profound underlying hyperlaxity, and in the revision setting.[85]

Biologic Agents in Anterior Cruciate Ligament Repair/Reconstruction

Growing interest has been placed on investigating biologic agents, both in the realm of ACLR and in the development of minimally invasive options to treat stable partial tears.[87] The main effort of these studies has been focused on two agents: platelet-rich plasma (PRP) and stem cells.

PRP is the most heavily used of the two agents in orthopedics, and its presence in literature reflects that being investigated in 22 of 23 studies included in a recent systematic review.[87-89] Overall, there is no consensus on the role and impact of PRP on ACL repair or reconstruction. However, a number of studies suggest that PRP may promote graft maturation over time, but this is still controversial and there are studies which fail to support this finding.[87,90,91] There is no demonstrated benefit toward bone-graft integration or prevention of bony tunnel enlargement.[87,92] Use of PRP in partial tears is still poorly understood and scarcely investigated in humans at this time. Recent canine studies suggest that PRP may reduce pain and improve range of motion and limb function, and it demonstrates evidence of repair with decreased synovitis on histologic examination compared to saline injection.[87,93] One major limiting factor in evaluation of PRP is the significant variability in harvest, preparation, and location of application/injection, as well as inherent variability in patient biology, impacting the composition and biologic activity of the concentrate.[92,94] Not only does the PRP compositions of platelets and leukocytes vary between individuals when using the same system, but it also varies for the same individual when collected at different times.[95] For this reason, some more recent systems attempt to standardize or even allow customization of PRP concentrates by use of flow cytometry.

Much public attention has been placed on the use of stems cells in regenerative medicine. However, their role in management of ACL injuries is highly debated and poorly understood. In DiMatteo's 2016 systematic review, only two studies evaluating the use of stems cells on partial ACL tears met their criteria: one looking at the effects of stem cells alone and the other in concert with PRP.[87,96,97]

In 2014, Silva *et al*. used MRI to assess the effect of adult noncultivated bone marrow stem cells on tendon-to-bone healing in the femoral tunnel in ACLR. Their findings suggest that adult noncultivated bone marrow stem cells do not appear to accelerate graft-to-bone healing in ACLR.[87,96]

Centeno *et al*. performed a prospective trial where patients were treated by fluoroscopic-guided intraligamentary injection of PRP, platelet lysate, and bone marrow-derived stem cells. Seven out of 10 patients demonstrated changes consistent with ACL healing on MRI evaluation at 3 months following the procedure.[87,97]

Some studies have begun to evaluate the comparative multilineage potential of mesenchymal stem cells from different tissues. In 2017, Ćuti *et al*. concluded that *in vitro*, mesenchymal stem cells derived from muscle tissue had greater innate capacity to enhance bone-tendon integration and graft ligamentization than those derived from the HT itself. They suggest that instead of stripping all the remnant muscle from the harvested HT autograft, that leaving some of the remnant muscle on the tendon may yield better graft maturation and integration.[98] An additional study compared the multilineage potential of stem cells derived from HT versus that from the native ACL. They concluded that stem cells derived from the ACL have a much higher multilineage potential than those from an HT graft and suggested that external stimuli are important for HT graft maturation and restoration of more normal ligamentous properties and function.[99]

Again, results investigating the use of stem cells are subject to a number of the same limitations as PRP regarding variable patient biology as well as heterogeneity of harvesting, preparation, and application techniques.

Pre and Postoperative Rehabilitation and Return to Play

The timing of ACLR can influence rehabilitation outcomes as early ACLR has been associated with delays in quadriceps recovery as well as a loss in range of motion. Several articles demonstrate reduced quadriceps strength at multiple intervals following early ACLR (postinjury days 0–7) compared to delayed reconstruction (postinjury days 8–21), as well as significant loss in terminal knee extension.[19,100,101] This highlights a growing trend in the use of preoperative rehabilitation. Preoperative rehabilitation should focus on preservation of quadriceps strength and knee range of motion as deficits in both of these parameters are associated with poorer functional outcomes.[19,102-104]

Structured rehabilitation of ACL ruptures is similar for patients whether being treated with reconstruction or nonoperative management with rehabilitation alone. In general, rehabilitation programs include cryotherapy (ice), gravity-assisted motion or continuous passive motion (constant mechanical movement by a machine), protective bracing, electrical neuromuscular stimulation, and exercises (i.e., isometric, isotonic, and isokinetic) aimed at strengthening, balance, proprioception, and on mitigating the inflammatory response.[31] Rehabilitation, whether used as definitive treatment or as a component of surgical intervention, typically uses a three-stage progressive program consisting of acute, recovery, and functional phases.[31,105] The acute stage is used both following acute injury and in the immediate postoperative period, and it aims to restore range of motion, maintain quadriceps strength as previously discussed, and reduce inflammation. The recovery phase typically lasts 3–6 weeks, with the goal of improving lower limb muscle strength and functional stability. The functional stage usually begins at 6 weeks postinjury or postoperatively and is directed at returning the patient to his or her previous levels of function/activity. The functional stage should also encompass efforts to reduce the risk of re-injury, a topic later discussed in injury prevention.[31,106]

Although rehabilitation typically follows this three-phase program, there is little consensus regarding the most effective rehabilitation protocol.[31,107] Similarly, no clear consensus exists regarding the acceptable timeframe for return to play. Early return to play has been associated with increased risk of graft failure as well as injury to the contralateral native ACL.[5] As such, recent trends favor a decelerated rehabilitation protocol with consideration of return to play in the realm of 8–12 months or longer postoperatively.[4,5]

While no standardized return-to-play protocol exists, studies suggest that return to play is safe when an athlete meets a specific set of clinical criteria; these include:

1. Time from surgery (8 to 12+ months)
2. Absence of pain and effusion
3. Knee range of motion comparable to the contralateral limb
4. A negative Lachman or pivot shift test
5. Successful performance of hop tests at >85%–90% the performance of the contralateral limb
6. Jump and landing tasks such as the drop vertical jump without evidence of dynamic valgus (a topic discussed in further detail in the injury prevention section).[4,5]

Risk Factors for Revision Anterior Cruciate Ligament Reconstruction

It is imperative that surgeons understand and address factors predisposing patients to ACL re-tear as failure rates of up to 14% for adults and 28% for males under 18 years of age are reported.[90,108,109]

Schilaty *et al*. reported that over a 20-year period, 6% of individuals had a second ACL tear, with 67% being in the contralateral knee, higher incidence of failure in females under 20 years of age, and are more often associated with use of HT grafts versus BPTB.[110] However, after multivariate analysis, only decreasing patient age and selection of allograft were associated risk factors for revision reconstruction.[111] Ho *et al*. report a 9.6% failure rate in the pediatric/adolescent population and an 8%

rate of contralateral ACL tears during their 12-year study period. They reported that BPTB grafts had the lowest failure rate and that graft choice was the strongest predictor of failure in multivariate analysis.[112] Analysis regarding graft type has found lower revision rates in skeletally mature individuals undergoing reconstruction with BPTB autograft when compared against HT autograft and HT allograft. However, differences between revision rates for HT allograft versus autograft failed to be statistically significant after controlling for confounding variables.[111,113]

Multiple studies have reported increasing age to be a protective factor against revision ACLR,[111,114] and the average time between primary ACLR and revision ACLR ranges from 1.5 to 3.5 years in the literature.[111,114-118] Some graft processing techniques as well as increased graft irradiation (>1.8 Mrad) have been associated with higher revision rates.[118] In a retrospective analysis, posterior tibial tunnel placement (placement 50% or more posterior to Amis and Jakob line) has also been associated with increased revision rates in those using a 70° "anti-impingement" tibial tunnel guide.[119]

It is also important to address relevant concomitant meniscal lesions, meniscocapsular separations, and aberrant bony morphology at the time of their ACLR.[85] Parkinson *et al*. identified that meniscal deficiency (medial > lateral) is the most significant risk factor associated with graft failure for single-bundle anatomic ACLR, with shallow, nonanatomic femoral tunnel placement and younger patient age being additional risk factors for failure.[120] Concomitant medial and lateral meniscal tears have been identified as independent predictors of increased lateral tibia subluxation.[121] This same group also identified that knees with failed ACLR are associated with more anterior tibial subluxation than those with primary ACL deficiency. Using previously reported thresholds of 6–10 mm of lateral compartment subluxation for a positive pivot shift, noting that between 11.1% and 37.5% of knees with failed ACLR may be in a "resting pivoted position."

Syam *et al*. demonstrated significantly higher radiographic evidence of OA in patients with documented tears of the posterior horn of the medial meniscus (PHMM). Further, they demonstrate that objective instability was higher in those with a deficient PHMM, which is in agreement with cadaveric studies demonstrating that sectioning of the PHMM is associated with loss of the "break stop" mechanism provided by the medial meniscus (this results in increased strain on ACL grafts).[122-127] Saltzman *et al*. reported that concomitant ACLR and meniscal allograft transplantation (MAT) can provide significant improvements in clinical outcomes and enhancement in objective knee stability. They also noted that concomitant ACLR and MAT were associated with an insignificant degree of radiographic joint-space narrowing changes – a 5-year survivorship of MATs is >80%.[128]

Increasing lateral tibial posterior slope (LTPS) has been associated with predisposition for native ACL tears in a number of studies. Christensen *et al*. reported an association between increasing LTPS and increased revision rates, with an LTPS average of 8.4° in the early failure group versus 6.5° in their control group. They reported an increasing odds ratio of re-tear which was statistically significant and directly related to the degree of posterior slope.[129,130] Slope decreasing tibial osteotomy influences translational forces across the ACL graft during axial loading and may be protective.[131] Arun *et al*. found that individuals undergoing tibial osteotomy at the time of ACLR with >5° correction to decrease posterior tibial slope reported significantly better functional scores.[131] However, Dean *et al*. reported that the use of an opening wedge proximal tibial osteotomy – in concert with posteromedially placed anteriorly angled osteotomy plate and anterior staple augmentation – failed to decrease sagittal tibial slope. They concluded that current osteotomy plate design and techniques are not effective at decreasing sagittal plane tibial slope.[132]

Re-revision cases have not yet been well studied, and risk factors for multiple revisions are poorly understood. However, it is reasonable to infer that obstacles in revision cases are magnified in subsequent revisions.[109] In a systematic review performed by Liechti *et al*., re-revision cases demonstrate higher rates of concomitant internal derangement such as meniscal and cartilage pathologies than in primary and revision cases, highlighting the importance of restoring ACL function and addressing concomitant pathology to minimize risk of failure and subsequent revisions.[109]

Anterior Cruciate Ligament Injury Prevention

Although cliché, it is said that the best injury treatment is prevention, and contemporary efforts regarding ACL injury have embraced this concept. Recent studies have not only sought to better understand the anatomical and biomechanical risk factors for ACL injury but also aimed at influencing modifiable risk factors.

Neuromuscular control is thought to play an important role in injury risk and has been identified as the most modifiable risk factor. Hewett *et al*. identified four neuromuscular imbalances that have increased risk for ACL injuries: ligament dominance, quadriceps dominance, leg dominance, and trunk dominance.[133,134] Increased dynamic valgus position and abduction loads in the lower extremity have been associated with increased risk of ACL injury in female athletes. These increased loads are often driven by core neuromuscular dysfunction, as well as lower limb asymmetry, defined as side-to-side differences in muscle strength, flexibility and recruitment pattern.[134-141] Neuromuscular training in females has been shown to increase dynamic knee stability in the laboratory setting and it translates to decreased incidence of noncontact ACL injury in female athletes.[134,142-145] Neuromuscular training facilitates adaptations which improve pre- and mid-stance neuromuscular activation patterns, which decrease joint motion and protect the ACL from high impulse loads sustained during performance.[134,144,146,147] Future efforts should be aimed at more sensitive and efficient screening of modifiable risk factors and pathologic biomechanics to allow for improved identification of high-risk athletes and the development of tailored interventions.[134]

It is well reported that emphasis on posterior chain muscle group strengthening such as the gluteus maximus, gluteus medius, gluteus minimus, and hamstings reduces the load to the ACL by controlling frontal plane motion and improving neuromuscular control.[133,134,148] Preadolescent or early adolescent female athletes seem to be the patients who may receive the greatest potential benefit from prevention programs.[149]

A number of options exist for employment of screening and prevention programs, but typical motion capture systems are expensive and require the use of multiple cameras and/or multiple markers. One potential solution to this issue is use of the Microsoft Kinect SDK, which is relatively much less expensive and does not require placement of markers on study subjects.[150,151] In 2014, Gray *et al*. found excellent correlation values or agreement between the Kinect motion capture system and the "gold standard" Vicon system. Their small cohort results were expanded in a larger scale model by Sherman *et al*. in 2016, by screening 180 healthy high school athletes. They conclude that the system could be safe, efficient (1.5 min/athlete evaluation), and effective at detecting dynamic valgus during drop vertical jump test, a position which places the athlete at risk for ACL injury.[151] Multiple studies conclude that use of the Kinect system is feasible for dynamic screening to identify individuals at risk for ACL injury as well as for targeted intervention.[133,150,151]

Summary

The treatment of ACL injury is a dynamic and evolving field. Strategies change as we gain a better understanding of the native knee kinematics, basic science of ligament healing, improved surgical techniques, better recognition of major causes of ACL surgical failure, injury risk detection, and primary prevention. It is important that we continue to reflect on where we have been and where we are going. Healthy debate is critical to analyze novel concepts and to learn from the success and failure of those who came before us. What is in and out in ACL surgery may change over time, but intellectual curiosity and the drive to safely improve patient outcomes are a unifying principle that remains constant.

Financial support and sponsorship

Nil.

Conflicts of interest

Benjamin T. Raines and Emily Naclerio have no conflicts to report. Seth L Sherman reports the following conflicts: ACL Study Group: board or committee member; American Journal of Orthopedics: editorial or governing board; American Orthopaedic Society for Sports Medicine: board or committee member; Arthrex, Inc.: paid consultant; research support; Arthroscopy: editorial or governing board; Arthroscopy Association of North America: board or committee member; Neotis: paid consultant; Regeneration Technologies, Inc.: paid consultant; Vericel: paid consultant; and Zimmer: research support.

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