CURRENT CONCEPTS REVIEW

Revision Anterior Cruciate Ligament Reconstruction (ACLR): Causes and How to Minimize Primary ACLR Failure

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Abstract

Anterior cruciate ligament (ACL) tears are a common orthopaedic injury, particularly in athletic populations. Primary ACL reconstructions (ACLR) have fairly successful outcomes; however, there is a subset of patients who experience failure or re-injury and require a technically challenging revision ACLR procedure. Knowledge of the clinically relevant ACL anatomy and biomechanics, including closely associated meniscal, ligament, and osseous structures, is fundamental for an anatomic revision ACLR. Comprehensive evaluation and diagnosis are also critical to identify the causes of primary ACLR failure and determine appropriate treatment(s). Although outcomes have improved over time, revision ACLR patients still experience sub-optimal outcomes compared to primary ACLR patients. This review will highlight the current concepts of anatomy, biomechanics, clinical evaluation, treatment, outcomes, and post-operative rehabilitation to optimize outcomes for revision ACLR procedures.

Level of evidence: V

Keywords: Anterior cruciate ligament, Multiple stage, Revision

Introduction

Anterior cruciate ligament reconstruction (ACLR) is a common orthopaedic procedure, with primary ACLR surgery success rates ranging from 75% to 97%.[1-3] Still, there remains a significant number of patients who experience primary ACLR failure. In a systematic review by Wright et. al, the ipsilateral anterior cruciate ligament (ACL) graft rupture rate was 5.8% after a minimum five-year follow-up to primary ACLR.[4] Magnussen et. al found a 7.9% ACL graft rupture risk after a 10-year minimum follow-up to primary ACLR.[5]

The causes of primary ACLR failure are complex and multifactorial. Factors that influence the risk for failure include: nonanatomic tunnel placement, graft selection, untreated concomitant meniscal or ligamental injuries at the time of index surgery, increased posterior tibial slope and coronal plane malalignment, rehabilitation, return to activity timeline, and re-injury.[6-9] There is not a single definition for a primary ACLR failure. Clinically, indications for a revision ACLR can be evaluated objectively by rotational laxity found on the pivot-shift test or graft rupture and subjectively by patient reports of persistent instability, pain, stiffness, or functional impairments.[3,10,11]

Revision ACLR failure rates have been reported to be three to four times higher than primary ACLR failure rates.[12,13] Recently, a meta-analysis found a revision ACLR graft failure rate of 6%, which is more comparable to primary ACLR failure rates.[14] However, despite some possible improvements, revision ACLR procedures still have sub-optimal patient outcomes.[14] Several analyses have reported that patients who undergo a revision ACLR have inferior clinician assessed knee function and patient reported outcomes compared to primary ACLR patients. [13, 15-17] Furthermore, Vap et al. recently reported re-revision ACLR rates of 0.4%, 3.0%, 6.5%, and 9.0% at one-, two-, five-, and eight-years follow-up after a first revision ACLR procedure, respectively. These findings demonstrate that re-revision ACLR patients are

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at a greater risk for procedure failure than primary ACLR patients.[18]

Returning to sport after undergoing a revision ACLR can be challenging. Glogovac et. al found the average time of return to sport (RTS) was 6.7 months to 12 months, with a 56% to 100% rate of return to any sport at any level and a 13% to 69% rate of RTS at preinjury level.[19] Kiran et al. reported 40.2% of patients who underwent a revision ACLR returned to preinjury level, while 34.7% of patients did not RTS after a mean nine-year follow-up.[20] Furthermore, patients who undergo re-revision ACLR experience poorer outcomes when considering the ability to return to one's pre-injury activity level, compared to primary ACLR patients.[21]

Therefore, when managing ACL tears, it is critically important for surgeons to first approach primary ACLR comprehensively to offer patients optimal chances for long term success and to prevent the need for a revision ACLR altogether. This purpose of this review is to highlight the findings of the current concepts of revision ACLR including anatomy, relevant biomechanics, clinical evaluation, treatment, outcomes, and post-operative rehabilitation.

Anatomy

The ACL is comprised of two functional bundles, the anteromedial (AM) and posterolateral (PL) bundles, which are named for their relative attachment on the tibia. There are several femoral and tibial landmarks that have been described to quantify the anatomy of the ACL. On the lateral femoral condyle, the ACL center inserts 8.5 mm anterior to the posterior cartilage margin and 6.1 mm posterior to the lateral intercondylar ridge [Figure 1]. Furthermore, the ACL center attaches 1.7 mm proximal to the bifurcate ridge, which courses between the femoral AM and PL bundle footprints [Figure 1]. On the tibial plateau, the ACL center attaches 10.5 mm posterior to the ACL ridge and 13.0 mm anterior to the retro-eminence ridge [Figure 2]. Additionally, the center of the ACL tibial footprint notably inserts 7.5 mm medial to the anterior horn of the lateral meniscus, which essentially puts it adjacent to the anterior horn of the lateral meniscus [Figure 2].[22,23]

The anatomical relationship between the tibial ACL insertion and the anterolateral meniscal root (ALMR) should be considered during tibial tunnel drilling, because the native ACL footprint overlaps with the ALMR. LaPrade et al. found that anatomic ACL tibial tunnel drilling resulted in significant loss of ALMR strength and attachment area.[24] Consequently, this type of iatrogenic injury may put patients at risk for altered knee joint load distribution and the consequent development of early osteoarthritis.[25] It has been reported that patients who underwent a revision ACLR had significantly higher rates of femoral tunnels being located more anteriorly and proximally than patients who did not.[26]

In summary, successful primary and revision ACLR are highly dependent upon a comprehensive understanding of the quantitative anatomical relationships of relevant landmarks. The overlapping insertion of the ALMR and the ACL tibial footprint must also be considered for optimal tibial tunnel placement that restores native knee anatomy while avoiding iatrogenic injury.

Biomechanics

Functionally, the ACL is the primary restraint to anterior tibial translation (ATT). It also stabilizes the knee during internal rotation. The AM and PL bundles assume the majority of load forces at different joint positions.[27-29] Gabriel et al. demonstrated that forces transmitted through the AM bundle were greatest at 60° and 90° of knee flexion, while forces transmitted through the PM bundle were greatest at full knee extension.[27,29] The forces in the AM bundle and intact ACL were almost equivalent at higher flexion angles (60° and 90°) and the PL bundle contributed negligibly to anterior tibial load force distribution at these higher flexion angles.[29] Zantop et al. found that resection of the AM bundle resulted in significant increased ATT at higher flexion angles, whereas PL bundle sectioning resulted in significantly increased

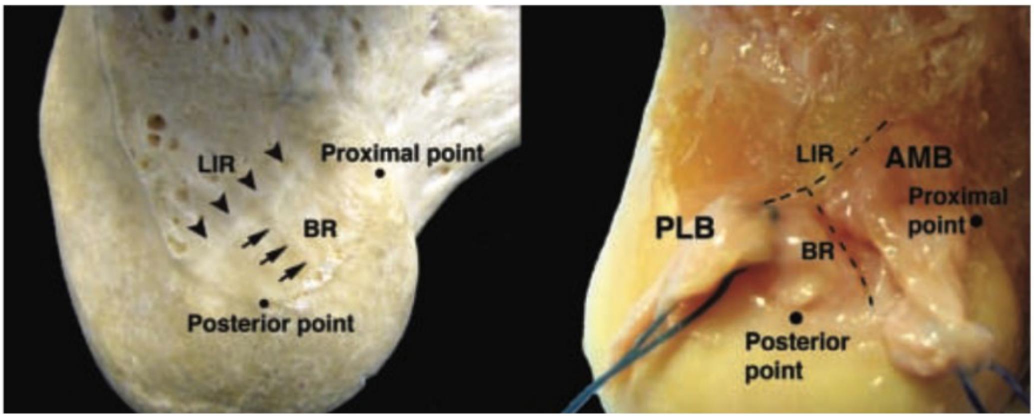

Figure 1. Skeletal (left) and cadaveric (right) specimens of lateral femoral condyles depicting important anatomical bony landmarks for the femoral ACL attachment. LIR, lateral intercondylar ridge; BR, bifurcate ridge; AMB, anteromedial bundle; PLB, posterolateral bundle. Reproduced with permission from AJSM Vol. 39 Issue 4, 743-752.

ATT at lower flexion angles It has also been reported that in response to a combined rotatory load, ATT was significantly increased in PL bundle deficient knees at 0° and 30° flexion, but not in AM bundle deficient knees.[30] Another biomechanical study by Goldsmith et al. reported no significant difference in ATT during pivot shift testing and to 88 N anterior tibial loading after performing anatomic SB and anatomic DB ACL reconstructions on cadaveric knees. It has been noted there were small (<3°), yet statistically significant, differences in ATT between SB and DB ACL reconstructions during internal rotation; however, these were likely not of clinical significance.[31]

Secondary Stabilizers to Anterior Tibial Translation and Anterolateral Rotation

Anterolateral Complex (ALC)

Recently, the anterolateral ligament (ALL) and iliotibial band (ITB) Kaplan fibers have gathered increased attention for the complementary functional role these anterolateral structures play in relation with the ACL. The ALL provides secondary stabilization by resisting ATT, internal tibial rotation, and the pivot shift.[32-34] In the setting of ACL deficiency, ALL and ITB Kaplan fiber injury results in significantly increased ATT, pivot shift, and internal rotation, with the ITB Kaplan fibers providing the primary stabilization for internal rotation at high flexion angles.[33]

Medial Collateral Ligament (MCL)

Concomitant MCL injuries occur in about 20% of ACL ruptures.[28,35,36] The MCL functions to provide valgus and external rotation stability.[37-39] Recent biomechanical studies report the superficial MCL is the principal medial structure providing anteromedial rotational stability.[40,41] The MCL injury severity grading is important when evaluating and determining the treatment for a combined ACL-MCL injury.[42] If an MCL injury persists, knee instability can result which increases ACL graft forces and the risk for ACLR failure.[10,43,44] Recently, Alm et al. reported the risk of revision ACLR failure was significantly associated with pre-operative medial knee instability after a minimum two-year follow-up.[45]

Lateral Meniscus (LM)

In an ACL-deficient knee, the LM posterior root provides secondary stability against ATT and internal rotation during pivoting. Furthermore, the LM posterior root attachment functions as the primary stabilizer for internal rotation at 75° and 90° flexion in ACL-intact and ACL-deficient knees. Loss of the LM posterior root attachment in ACL-deficient knees results in significantly increased ATT and internal rotation.[46] A biomechanical study found that in ACL-intact and ACL-deficient knees, longitudinal tears in the posterior horn of the LM significantly increased in size after 500 loading cycles, with 28.7% and 26.1% propagation of the tears in ACL-intact and ACL-deficient knees, respectively. Compared to ACL-intact knees, there were significantly higher bony contact forces at the tibiofemoral joint in ACL-deficient knees at 30° flexion after tear propagation.[47] A recent study found concomitant LM posterior root tears in 12.2% of primary ACLR cases and 20.5% of revision ACLR cases 48; therefore, proper diagnosis and repair of lateral meniscus root and posterior horn tears are vital to prevent ACLR failure and the development of lateral compartment arthritis.

Posterior horn of Medial Meniscus (PHMM)

Meniscal ramp and PMHH injuries are commonly

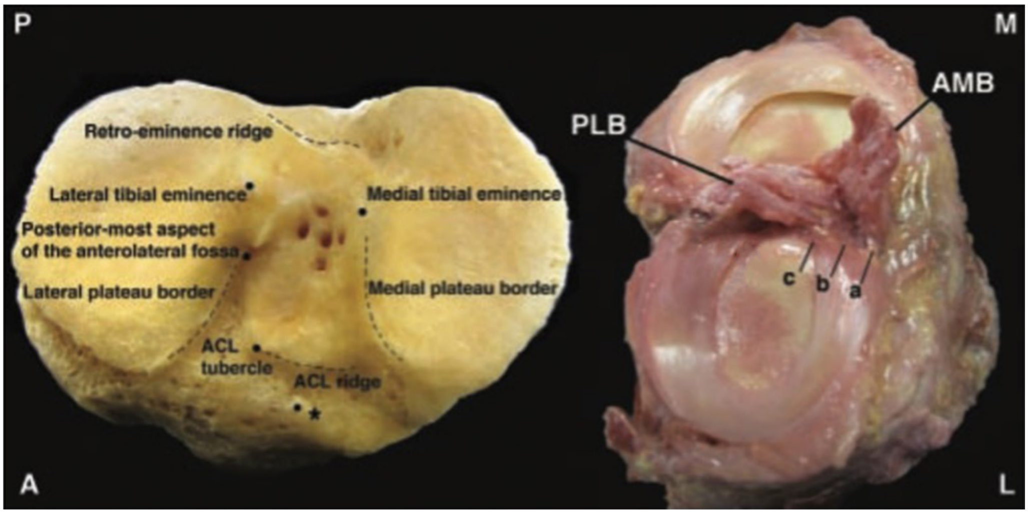

Figure 2. Superior views of skeletal (left) and cadaveric (right) tibial plateaus illustrating pertinent anatomical landmarks for the ACL attachment on the tibia. The cadaveric specimen also highlights the relationship between the tibial ACL and anterior horn of the lateral meniscus attachment sites. The AMB and PLB of the ACL overlap with the (a) anterior, (b) middle, and (c) posterior attachment sites of the anterior horn of the lateral meniscus. AMB, anteromedial bundle; PLB, posterolateral bundle. Reproduced with permission from AJSM Vol. 39 Issue 4, 743-752.

observed with ACL tears. An analysis by Magosh et al. of 358 primary and revision ACLR procedures found concurrent meniscal injuries in 67% of ACL injuries, where 52% of those injuries were a ramp tear of the PHMM and/or a lesion to the posterior root of the LM.[49] Functionally, the PHMM provides secondary stability against ATT.[50] Therefore, when the PHMM is torn and left untreated, an ACL graft is at risk for stretching out over time due to the increased anterior translation forces on the graft. Furthermore, injuries to the meniscocapsular and meniscotibial attachments of the PHMM can result in increased ATT, pivot shift, and internal and external rotation in the setting of ACL deficiency.[51] This finding is supported by a recent study that reported increased rotational laxity (evidenced by higher pivot shift test grade) in patients who had a combined medial meniscus ramp lesion and ACL injury compared to an isolated ACL injury.[52]

Posterolateral Corner (PLC)

Injuries to the PLC most often occur simultaneous with cruciate ligament injuries.[53] The major static stabilizing structures of the PLC are the fibular collateral ligament (FCL), popliteus tendon, and popliteofibular ligament. In an ACL-deficient knee, the PLC provides secondary stabilization to ATT at early flexion angles; a function that is very minimally present in ACL-intact knees.[54] LaPrade et al. studied the biomechanical effects of sectioning PLC structures on ACL graft force. It has been reported that ACL graft force was significantly increased after sectioning the FCL at 0° and 30° flexion with varus loading and was further increased at 0° and 30° flexion with coupled varus loading and internal rotation.[9] These findings demonstrate that untreated PLC injuries during primary and revision ACLR cases leads to an increased risk for ACL graft failure.

Coronal and Sagittal Plane Alignment

Biomechanical studies have demonstrated a linear relationship between increased posterior tibial slope (PTS) and forces in an ACLR graft, which is further potentiated by the presence of a posterior medial meniscus root tear.[55,56] Bernholt et al. reported an increased incidence of LM posterior root tears in primary ACLR patients with significantly increased lateral and medial PTS.57 Another study found that patients who experienced a contralateral ACL injury after revision ACLR had significantly increased lateral PTS, while patients with graft failure after revision ACLR had significantly increased lateral and medial PTS.[58] A PTS ≥ 12° strongly predicts repeat ACL injury after primary ACLR, especially in patients ≤ 18 years.[59] Identification of concomitant meniscal injuries and an understanding of their association to increased PTS may guide surgical planning, especially for revision ACLR patients.[6]

Proximal tibial osteotomies are often utilized in revision ACLR cases to correct tibial slope and mitigate the risk of ACL graft failure. A recent cadaveric study demonstrated that correction of knees that had natively increased PTS and varus alignment with a combined varus and anterior closing-wedge osteotomy resulted in significantly decreased ACL graft forces compared to the native knee, with mean 33% and 58% decreases at 200 N and 400 N axial joint loading, respectively.60 Identifying increased PTS as a cause of primary ACLR failure and performing correction anterior closing-wedge osteotomy during revision ACLR will likely offer patients improved long-term outcomes with a stable ACL graft.

Posterolateral tibial impaction fractures often occur with ACL tears, depending on the specific mechanism of injury. A recent analysis by Bernholt et al. reported a 49.3% prevalence of posterolateral tibial plateau impaction fractures and a 25.9% prevalence of lateral femoral condylar impaction fractures in patients at the time of primary ACLR.[61] Furthermore, posterolateral tibial plateau impaction fractures were significantly associated with the presence of medial meniscal ramp lesions, whereas femoral condylar impaction fractures were significantly associated with lateral meniscal tears, lateral meniscus posterior root tears, and medial meniscal ramp lesions.[61] Bernholt et al. also found that patients with concomitant posterolateral tibial plateau impaction fractures (type IIIB) with primary ACL tears independently predicted a high-grade pivot shift on exam under anesthesia (odds ratio, 2.3) and inferior Lysholm scores two years postoperative after ACLR.[62] Understanding the associations between meniscal tears and posterolateral tibial plateau impaction fractures with ACL tears may improve their diagnosis and treatment. Subsequently, the risk of ACL graft failure may be decreased.

Clinical Evaluation

Precisely identifying all possible causes of ACLR failure is fundamental for a successful revision ACLR. Generally, the causes of a failed ACLR are broadly categorized as technical (surgical) errors, failure of graft incorporation, and traumatic re-injury.[8] The pre-operative as-sessment should be approached systematically, and include a thorough patient history, physical examination, and imaging studies. Pache et al. proposed a clinical work-up algorithm for ACLR failure evaluation. This algorithm provides a framework for determining optimal staging and concurrent procedures for revision ACLR based on a methodical evaluation of the following: pa-tient history, physical examination findings, imaging, assessment of risk factors, primary ACLR technique/outcomes, bone morphology, and concomitant injuries.[10]

History and Physical Examination

A detailed history of the patient's symptoms, mechanism of injury, timeline of graft fail-ure, activity level, and functional/sport goals must be discussed. In addition, a comprehensive report on the primary ACLR procedure including the index injury mechanism, symptoms, opera-tive report, imaging, post-operative rehabilitation, and RTS should be obtained. All prior surgical procedures, knee pathologies, and risk factors for ACL tears should also be discerned. The physi-cal exam should begin with detailed inspection of the knee looking for placement of prior inci-sions, swelling, and signs of infection.[63] Quadriceps circumference should also be noted.[12] The patient's gait should be evaluated to detect possible limb malignment and range of motion should also be assessed.[12,63] The Lachman test is the most useful maneuver to diagnose an ACL injury, as this test has both high specificity and high sensitivity in detecting ACL ruptures.[64] A positive Lachman test is indicated by increased ATT and a soft endpoint with the knee flexed at 20° to 30°.[64] The pivot shift test is also performed, with reported specificity rates as high as 98%, but a poor sensitivity of 24% due to patient guarding.[64] Most isolated ACL tears will have a 2+ pivot shift test, while an explosive 3+ pivot shift test should alert one to the high probability of other concomitant pathology contributing to the increased motion. Furthermore, varus and valgus stress testing at 0° and 30° flexion is used to evaluate the integrity of the collateral ligaments.[12,63] Finally, the posterior drawer test and dial test should be used to assess for concomitant posterior cruciate ligament and PLC injury, respectively.[12,63] All examinations should be completed on both the injured and contralateral knee to allow for side-to-side comparisons.

Imaging Studies

Several radiograph views should be obtained including anteroposterior, lateral, Rosen-berg, sunrise, and long leg alignment.[10] Assessment of tunnel positioning, existing hardware, PTS, presence of osteoarthritis, and varus/valgus limb malalignment is performed. Varus and valgus stress radiographs may be utilized to assist with diagnosis of suspected concomitant pos-terolateral and medial knee injuries, respectively [Figure 3].[65,66] A CT scan is the recommended imaging modality to evaluate index surgery tunnel size and for tunnel enlargement (osteolysis) [Figure 4].[67] An MRI is also important to assess the primary ACLR graft and to determine if concurrent meniscal, ligamental, and chondral injuries are present.[10,63,68]

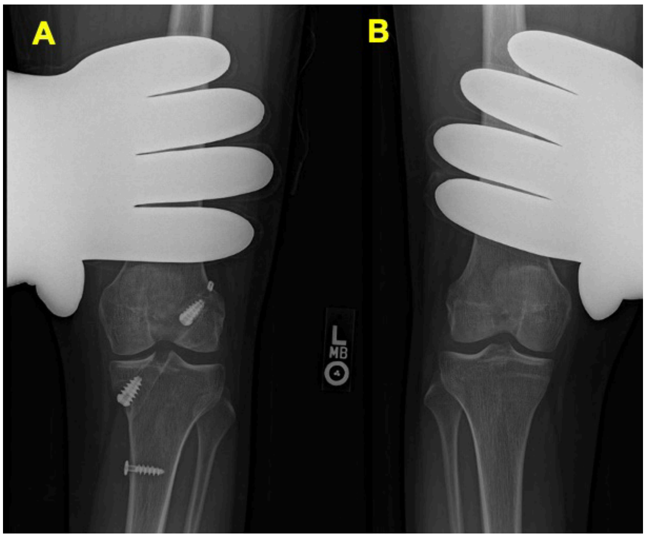

Figure 3. (A) Left knee varus stress radiograph from a revision ACLR patient case. (B) Healthy right knee varus stress radiograph from the revision ACLR patient case, which was used to compare to the post-operative knee. Stress radiographs can be used during initial patient evaluation to determine if concomitant posterolateral and medial knee injuries are present. They can also be used post-operatively in combination revision ACLR and fibular collateral ligament reconstruction cases to confirm that pre-operative gapping has been eliminated and that the revision ACL graft is stable.

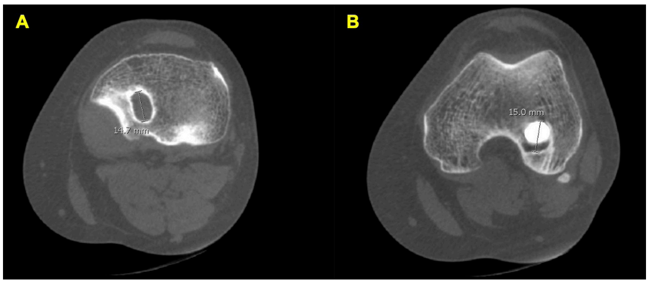

Figure 4. (A) Axial plane computed tomography (CT) scan demonstrating tunnel enlargement (≥14 mm) in the tibia, with diameter measurement. (B) Axial plane CT scan demonstrating tunnel enlargement (≥14 mm) in the femur, with diameter measurement.

Treatment Rationale

Graft Selection

ACL reconstruction graft options include ipsilateral or contralateral bone-patellar tendon-bone (BTB) autograft, ipsilateral or contralateral hamstring or quadriceps autograft, and BTB or soft tissue allograft. In general, autografts are preferred over allografts for revision ACLR. A large prospective registry study found that patients who received BTB autografts during primary ACLR had a significantly decreased risk of requiring a revision ACLR, compared to patients with a hamstring autograft.[7] Recently, Winkler et al. reported the use of quadriceps tendon auto-grafts during revision ACLR has significantly increased from 2010-2014 to 2015-2020.[69] The study did acknowledge a slight over-representation of quadriceps tendon autograft use in their study population; however, they importantly noted several recent studies indicating higher failure rates for hamstring tendon autografts and lower failure rates for quadriceps tendon autografts in ACLR.[69] A recent MARS group study examined revision ACLR outcomes after six years follow-up. They reported that patients with a BTB autograft ACLR had higher activity levels (measured by Marx Activity Rating Scale) and were 4.2 times less likely to experience graft rupture than patients who had a BTB allograft. There were no significant differences in rate of graft rupture between BTB autograft and soft tissue autographs or allografts. In total, 5.8% of patients experi-enced graft rupture; 3.5% of patients with autografts and 8.4% of patients with allografts.[70] A meta-analysis of 32 studies found that autografts had decreased laxity, complication rates, and re-operations after revision ACLR, compared to allografts. However, the study noted similar out-comes when excluding irradiated allografts from analysis.[71] Another meta-analysis reported simi-lar graft failure after revision ACLR for autografts and allografts, with rates of 4.1%

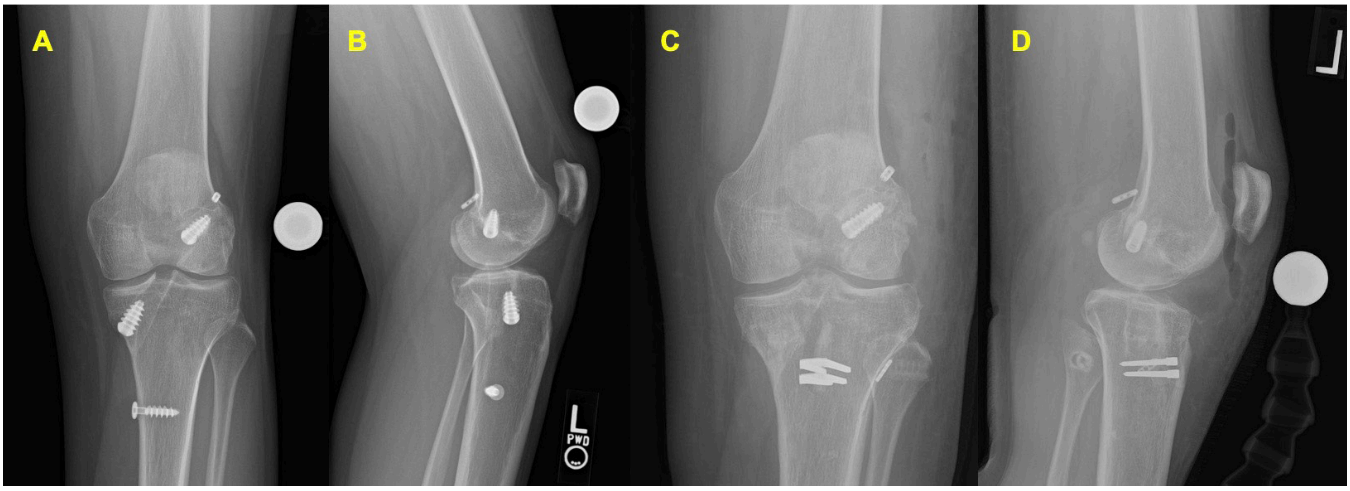

Figure 5. Pre-operative (A) anteroposterior (AP) and lateral (B) view radiographs of a left knee revision ACLR case with non-anatomic tunnels and poor hardware placement. Post-operative (C) AP and lateral (D) radiographs of the left knee after revision ACLR demonstrating anatomic tunnels and good hardware placement.

and 3.6%, respectively.[14] Graft options for revision ACLR may be limited depending on the type of graft that was used in the primary ACLR and other factors, so selection should be tailored to optimize each patient case.

Indications for Single-Stage versus Two-Stage Revision ACLR

Single-stage revision ACLR can be performed when all of the following criteria are met: preexisting femoral and tibial tunnels are anatomically positioned on the native ACL footprints, sufficient bone stock is present around both tunnels, tunnel diameter < 14 mm, or a nonanatomic preexisting tunnel that would not obstruct the anatomic placement of a revision tunnel.[72] A two-stage revision involves an initial tunnel bone grafting procedure, accompanied by debridement and hardware removal, followed by the revision ACLR four to six months after once the bone grafted tunnels heal.[72] Indications for two-stage revision ACLR include fulfilling one or more of the following criteria: presence of tunnel enlargement (tunnel diameter ≥14 mm), inadequate po-sition of existing tunnels that risks overlap with anatomic revision tunnels which leads to poor graft incorporation, insufficient tunnel bone stock, and inability for the ACL graft to be anatomi-cally placed or secured during a single stage procedure [Figure 5].[10,72] Additionally, when the sagittal plane of the PTS is ≥ 12°, an anterior closing wedge tibial osteotomy may be indicated. The objective is to reduce the posterior tibial slope to 6° to 8° or less, 6 prior to performing the revision ACLR [Figure 6].

Surgical Technique

Revision ACLR is a technically demanding procedure because the surgeon often needs to address several different causes of primary ACLR failure. Several techniques may be required, including repositioning tibial and/or femoral tunnels to anatomic placement, repairing concomi-tant ligament or meniscal injuries, performing an anterior closing wedge osteotomy to correct PTS, or performing a coronal plane osteotomy for valgus or varus malalignment.

A thorough examination under anesthesia of both the operative and nonoperative knee should be performed to verify physical exam findings (Lachman test, pivot shift test, var-us/valgus stress testing, and range of motion) and to elicit any undetected concomitant ligamen-tous injuries.[63-73] Anterolateral and anteromedial portals are made and routine arthroscopy is per-formed to further evaluate the knee joint for meniscal and chondral integrity, scarring, tunnel po-sition, and hardware placement.63 Next, remnants of the previous ACL graft and scar tissues are debrided.[73]

Single-Stage Revision

If the revision ACLR will be completed in one stage, the

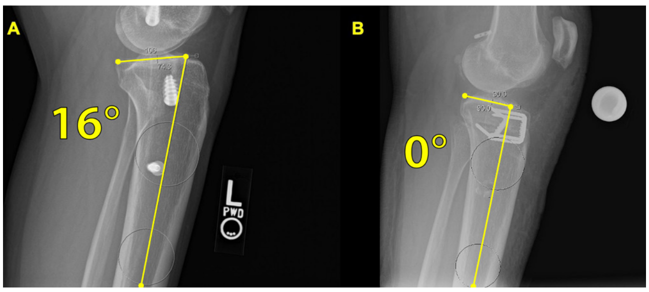

Figure 6. (A) Sagittal view radiograph of a failed primary anterior cruciate ligament reconstruc-tion case. This image demonstrates an increased posterior tibial slope (≥12°), which was an indi-cation for this patient to undergo an anterior closing wedge tibial osteotomy to correct the posterior tibial slope. (B) Postoperative day 1 radiograph following the anterior closing wedge tibial osteotomy, showing correction of the posterior tibial slope. This procedure was performed as stage one of a two stage revision ACLR.

Figure 7. Intraoperative photograph during stage two of a revision ACLR illustrating the use of a tibial guide to prepare the anatomic revision tibial tunnel. The bone grafted tunnel is used as the landmark for tunnel drilling.

surgical technique proceeds sim-ilar to a standard ACLR. As noted, concomitant injuries to secondary stabilizing structures pre-dispose patients to early ACL graft failure and poorer knee kinematics; therefore, appropriate surgical invention for those injuries should also be concurrently performed. Previous tunnels can be used as landmarks if determined to be in anatomic position pre-operatively. When a revision femoral tunnel is needed, the native ACL footprint is identified, and a bur hole is used to create a landmark midway between the AM and PL bundle attachments and posterior to the lateral inter-condylar ridge. For the tibial tunnel, the ALMR is utilized as the landmark for the native ACL footprint when the remnant ACL graft tibial stump is undetectable. The femoral and tibial tun-nels are reamed in the standard manner, and the ACL graft is fixed with titanium interference screws using an anterograde approach. Finally, an arthroscopic evaluation to validate the ACL graft is taut and a Lachman test should be performed to confirm restoration of stability.[72]

Two-Stage Revision

After initial soft tissue debridement, concomitant meniscal and chondral injuries are re-paired. Next, the revision femoral tunnel is prepared while removing previous fixation hardware and any remaining soft tissue. Similarly, the revision tibial tunnel is made by first removing pre-vious hardware through an incision over the existing tibial tunnel. Then the tibial tunnel is reamed, and soft tissue within the tunnel is debrided. Femoral and tibial tunnel bone grafting procedures are performed next, and the final ACL reconstruction will take place at a minimum four months later to allow for adequate bone graft healing [Figure 7, Figure 8].[72] Pearls and pit-falls of revision ACLR surgical technique are summarized in [Table 1].

Combined ACLR and ALC Treatment

Recently, there has been a re-emergence of interest in the literature regarding the clinical efficacy of combined ACLR and ALC procedures, such as anatomic ALL reconstruction (ALLR) and lateral extra-articular tenodesis (LET) [Figure 9]. Revision ACLR is a primary

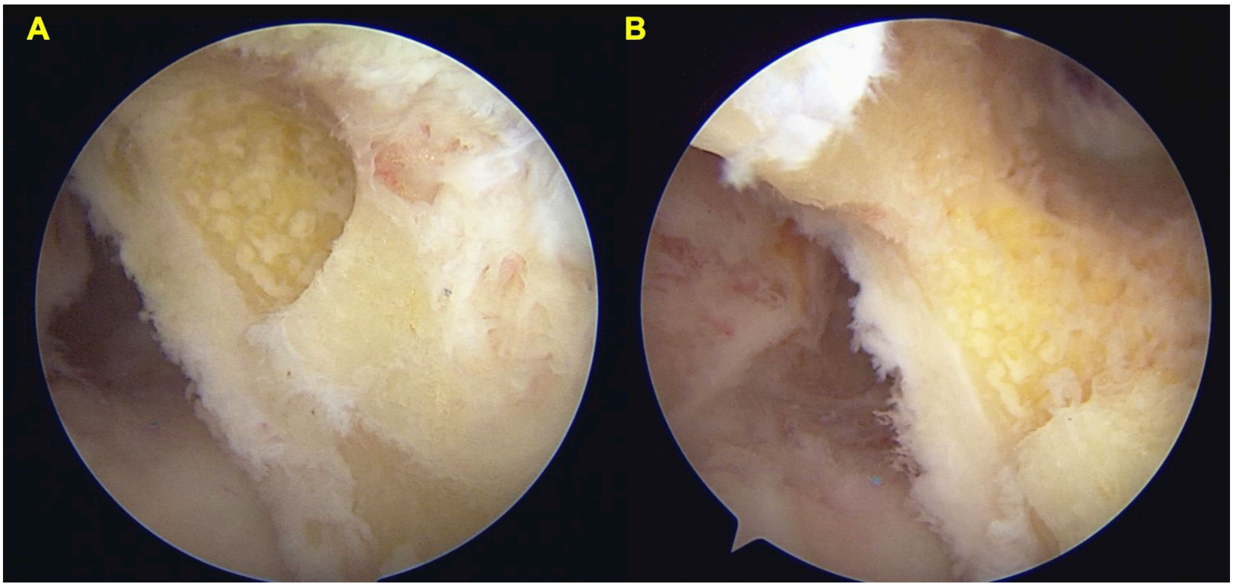

Figure 8. (A) Intraoperative photograph during stage two of a revision ACLR. This image demonstrates adequate healing of the femoral tunnel bone graft, prior to drilling of the revision femoral tunnel. (B) This intraoperative image shows the revision femoral tunnel after drilling and reaming.

Table 1. Pearls and pitfalls regarding the surgical technique for ACL reconstruction are highlight-ed here

Pearls	Pitfalls
Drill femoral tunnel two to three mm more anteriorly to the center of the femoral ACL attachment	Concomitant meniscal ramp or root lesions should be identified and treated
Use the anteromedial portal to confirm tibial tunnel placement	Avoid neglecting concomitant injury of other ligamentous structures
Use the ALMR as the landmark for correct tibial tunnel placement	Avoid breaking out the back of the femoral tunnel due to previous bony removal
Check for graft impingement intraoperatively	Ensure there is no intercondylar notch roof impingement from residual osteophytes

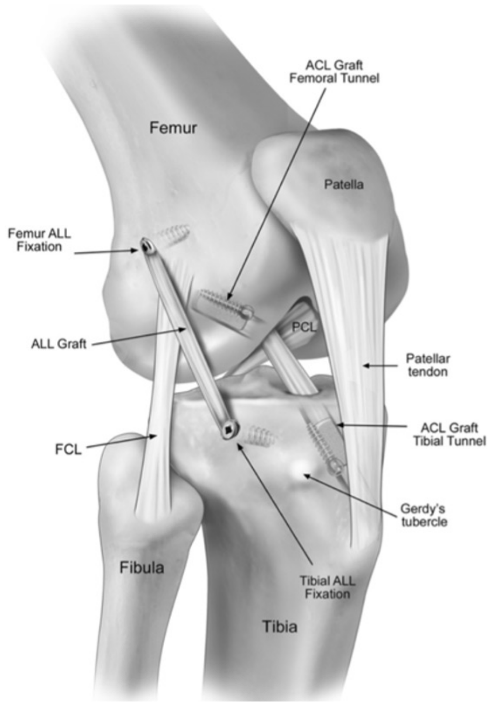

Figure 9. Illustration of a combined ACL and anterolateral ligament reconstruction (ALLR). Re-produced with permission from AJSM Vol. 46, Issue 5, 1235-1242.stage revision ACLR.

indication for performing ALLR.[34] Winkler et al. reported that LET was performed in 31% of revision ACLR cases.69 A biomechanical study found that in ACL and ALL-deficient knees, combining ACLR with ALLR or LET achieved similar results in terms of restoring knee stability during ATT and internal rotation, compared to ACLR alone.[74] In a recent systematic review, Littlefield et al. re-ported that, compared to isolated ACLR, combined ACLR and ALLR provided significantly de-creased ACL graft failure rates and superior patient reported outcomes.[34]

Outcomes

Single-Stage versus Two-Stage Revision

There are limited studies that directly compare outcomes between single-stage and two-stage re-vision ACLR. A study by Mitchell et al. found no significant difference in failure rates between single-stage (10.3%) and two-stage (6.1%) revision ACLR. The study also reported that both groups had significantly improved patient reported outcomes postoperatively (as measured by SF-12 PCS, WOMAC, Lysholm, and Tegner scores) and notably, there were no significant dif-ferences between the groups.[72] A recent systematic review reported the mean failure risk for sin-gle-stage and two-stage revision ACLR were 7.5% and 4.1%, respectively.[75] These findings sug-gest that similar outcomes can be achieved with appropriate procedure selection.

Identification of Patients At-Risk for ACL Graft Failure

Early identification of predictors and risk factors, especially those that are amendable, for ACLR failure may improve long-term patient outcomes. Ziegler et al. reported that patients who under-went a revision ACLR had a significantly increased Beighton score, lateral posterior tibial slope, anterolateral and anteromedial tibial subluxation, side-to-side quadricep circumference differ-ence, and family history of ACL tear, compared to a primary ACLR only group. Furthermore, the study found that 28.8% of revision ACLR patients had concomitant lateral meniscus root tears.[76] The MARS group reported that 11% of revision ACLR patients had a subsequent surgery at two years follow-up, with 19% of those surgeries being a re-revision ACLR.[77] These findings underscore the necessity of a comprehensive assessment and technical approach, starting at the primary ACL injury, for the prevention of ACL graft failure.

Another current consideration regarding the risk for ACL graft failure is whether the pri-mary ACLR procedure was performed with a SB or DB technique. These techniques have been widely debated for their ability to restore native knee kinematics and clinical efficacy. DB ACLR has been found to yield more favorable objective outcomes including fewer graft failures and reduced anteroposterior and rotatory laxity, compared to SB ACLR. Short-term patient reported outcomes were not found to differ between groups.[10,78] However, a more recent randomized con-trolled trial with a five-year follow-up found no significant difference in the Lachman test, pivot shift test, anteroposterior translation in neutral position and internal and external rotation, or pa-tient reported outcomes (measured by IKDC 2000) between DB and SB ACLR groups.[79] Of 22,460 patients in the Swedish National Knee Ligament Register, Svantesson et al. found a high-er risk for revision ACLR in patients who underwent primary ACLR using the SB technique, compared to the DB technique.[80]

Development of Osteoarthritis

Posttraumatic osteoarthritis (PTOA) is an established complication after the occurrence of ACL tears, with a 51.6% likelihood of development 20 years after ACLR.[81-85] The current literature indicates that anatomic ACLR (classified by AARSC score ≥8) was associated with decreased prevalence of osteoarthritis compared to non-anatomic/non-specified ACLR after 15 years fol-low-up.[86] A meta-analysis found that patients who underwent primary ACLR, compared to revi-sion ACLR, were half as likely to develop tibiofemoral osteoarthritis (determined by radio-graph).[15] Additional long-term studies evaluating the risk for developing PTOA in revision ACLR patients are needed.

Postoperative Rehabilitation

There is limited data on post-operative rehabilitation, and no standardized protocol exists for revision ACLR. In general, rehabilitation for revision ACLR should follow a similar protocol to primary ACLR, although the progression is slower and the timeframe for return to full activity is typically extended to a minimum of nine months postoperative to allow for biological incorporation of one's graft(s), which prevents early ACL graft failure.[10,72] Additionally, two-stage revi-sion ACLR patients should have a slower advancement to high-load muscular strength training and full RTS, compared to single-stage patients.[72] Key elements of rehabilitation, especially for athletes seeking RTS, include supportive management of patient expectations and adherence to a rehabilitation program. Della Villa et al. reported that rehabilitation compliance was significantly associated with RTS at pre-injury level after revision ACLR. The study found that 86% of fully compliant patients returned to their pre-injury level, compared to 45% of non-compliant pa-tients.[87] However, the significance of these results may be limited in clinical generalizability be-cause the study only included 79 patients with 78% males. Strength and functional testing at nine to 12 months post-surgery is used to determine readiness for RTS.[63] Several recent studies high-light the potential benefits for assessment of psychological readiness for RTS as part of a com-prehensive approach to ACLR rehabilitation, although data is limited for direct application to revision ACLR.[88-90]

The overall efficacy of functional bracing remains controversial in the literature, and most studies do not support use of post-operative bracing.[91-96] LaPrade et al. found that in healthy patients, a dynamic force brace better replicated the dynamic, physiological ACL forces across changing flexion angles, compared to a static force brace.[94] It has been suggested that a dynamic functional brace may aid in preventing revision ACL graft failure; however, there are no robust studies evaluating this clinical outcome to date. In a recent systematic review of clinical practice guidelines, it was reported that immediate knee mobilization in conjunction with strength and neuromuscular training are recommended, whereas functional bracing and continuous passive motion are not supported after ACLR.[96] Importantly, post-operative rehabilitation for revision ACLR should be individualized based on factors unique to each patient condition.[12] It is the cur-rent practice of some providers to use an ACL brace postoperatively through the first competitive sports season.

A revision ACLR procedure is complex and requires appreciation of the relevant anatomy and kinematics. An improved understanding and application of assessment of factors that cause ACL graft failure, such as surgical technique and untreated concomitant meniscal and ligamen-tous injuries, will likely lead to more successful outcomes for primary ACLR. Subsequently, this may prevent patient advancement to revision ACLR altogether. Nonetheless, if failure or recur-rent trauma occurs, revision ACLR requires an even more diligent and systematic approach. Through clinical assessment and radiographic evaluation, all causes of primary ACLR failure should be identified and addressed surgically. ACL revision also frequently occurs with con-comitant injury. Combined revision ACLR and ALLR or LET procedures may improve patient outcomes; however, single-stage and two-stage revision ACLR have demonstrated comparable patient outcomes when all other concomitant pathologies were surgically addressed. Appropriate patient counseling and management of expectation is important, as revision ACLR poses signifi-cant challenges for recovery and RTS.

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