Review Article

Principles for optimizing anterior cruciate ligament reconstruction outcomes in elite athletes: a review of current techniques

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Abstract: Anterior cruciate ligament (ACL) tears are one of the most common sport-related injuries and occur in greater than 3% of athletes in a four-year window of sports participation. Non-contact injuries are the most common mechanism for ACL injury in elite-level athletes, especially with increased valgus and external rotation of the knee when loading eccentrically in flexion. Because of the immense toll these injuries and their recovery take on athletes especially, optimal treatment has been a subject of great interest for some time. Many ACL reconstruction (ACLR) and repair techniques have been implemented and improved in the last two decades, leading to many surgical options for this type of injury. The surgical approach to high-level athletes in particular requires additional attention that may not be necessary in the general population. Important considerations for optimizing ACL treatment in high-level athletes include choosing repair *vs.* reconstruction, surgical techniques, choice of auto- or allograft, and associated concomitant procedures including other injuries or reinforcing techniques as well as attention to rehabilitation. Here, we discuss a range of surgical techniques from repair to reconstruction, and compare and contrast various reconstructive and reinforcing techniques as well as associated surgical pearls and pitfalls. Good outcomes for athletes suffering from ACL injury are attainable with proper treatment including the principles discussed herein.

Keywords: Anterior cruciate ligament (ACL); reconstruction; repair; graft

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Introduction

Anterior cruciate ligament (ACL) tears are one of the most common sport-related injuries, occurring in over 200,000 patients per year in the United States. Greater than 3% of athletes sustain an ACL tear within a 4-year window of sport participation and the incidence of ACL tears continues to rise for all levels of competition, a trend that includes elite athletes (1-5). Females are at increased risk for ACL injury and women's gymnastics, soccer and basketball represent three of the four highest-risk sports, behind American football (3,6). Furthermore, ACL injuries in elite athletes have been found to occur at increased rates in competition versus practice. There is a reported 20-fold increase in the ACL match play injury rate in European professional soccer compared to practice, with similar findings being reported in National Collegiate Athletic Association (NCAA) Football and the National Football League (NFL) (7-9).

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The frequency of dynamic, "high risk" movements in sports affects the risk of ACL injury in elite level athletes. A study by Kobayashi *et al.* reviewed the mechanisms of ACL injury in 1,700 patients and reported that noncontact injury was the most common mechanism for ACL tears. The authors also reported dynamic alignment in valgus and external tibial rotation to be a significant risk factor at the time of injury, resulting in significant strain to the ACL during the loading phase of knee flexion (9).

Patient outcomes for all-inside ACL reconstruction (ACLR) techniques are generally quite favorable, but have been observed to vary based on sport type. A retrospective study by Mai *et al.* found that ACLR in NFL athletes leads to a worse prognosis compared to other professional sports, with decreased on-field performance and shorter overall career length. In comparison, ACLR in NHL athletes was associated with the most favorable outcomes based on the same criteria. The physical demands imposed on the ACL graft during competition may explain these differences. Running and cutting in American football subject the surgically reconstructed knee to increased forces and could result in increased knee laxity, graft strain and return to sport (RTS) time compared with other sports which are less reliant upon these movements (10). This demonstrates the need not only for adherence to the full length of ACLR RTS protocol, but also the potential desirability of tailoring RTS protocol to individual sport demands.

The treatment of ACL rupture in elite level athletes poses a unique challenge because the patient must be able to return to sport at the same level of performance. Marginal postoperative changes in clinical or functional outcomes, which would not substantively affect return to activity in the general population, may result in decreased statistical performance and shorter careers. Return to "near-optimal" performance may not be sufficient. The current literature on ACLR outcomes in elite athletes is mixed. A recent systematic review found that 83% of professional athletes returned to a similar level of sport following ACLR. However, other studies have found decreased statistical performance and fewer starts for professional soccer players with ACLR (4,11,12). The variability in outcomes may be explained by the range in treatment options, graft selection, ACLR techniques, individualized anatomy of the patient, and the method and rigor of post-operative rehabilitation programs. The aim of this article is to summarize the existing techniques and principles used to achieve optimal results for ACLR in elite level athletes.

Graft selection for elite athletes

The ideal graft for ACLR in elite athletes should reproduce the anatomical and biomechanical properties of the native ACL, establish robust fixation, and facilitate rapid biologic integration (1). Beyond graft choice, promising innovations in orthobiologics have aimed to accelerate the ligamentization and osseointegration of grafts using techniques such as autologous tissue-engineered polyethylene terephthalate, but more research is needed in human models (13). Numerous studies have evaluated allogenic, synthetic, and autogenous grafts based on these guiding principles. However, despite the preponderance of literature on the subject, no current graft fulfills these criteria to the extent of the native ACL, and there remains no gold standard for anatomical ACL graft choice (14,15). Therefore, it is the surgeon's responsibility to evaluate the advantages and disadvantages for each graft and make an optimal selection based upon the patient's sport, individualized anatomy, and history of previous ACLR (1,12).

Bone-patellar tendon-bone (BTB) autograft

BTB autograft (*Figure 1*) is widely considered the premium graft choice for ACLR in elite athletes, 68% of Major League Soccer (MLS) team orthopedic surgeons prefer single-bundle BTB for ACLR and similar trends have been reported for the surgical treatment of NFL, NHL and US Olympic Ski and Snowboard athletes (16-19). Many surgeons prefer a BTB autograft due to its significant stiffness and tensile strength, which has been reported to exceed that of the native ACL (20). Past studies have reported decreased anterior knee laxity following BTB autograft compared to other autografts (20-22). The BTB autograft is also favored because the graft results in more rapid and durable bone integration compared to soft tissue grafts, decreasing the risk of future ACL revision (1,12). A study by Gifstad *et al.* found that BTB autografts resulted in significantly decreased risk of revision compared to ACLR with hamstring (HS) autografts in 45,998 patients with primary ACLR (23).

Despite these advantages, BTB autografts have been linked to increased complication rates when compared to other graft types (1). A majority of complications occur during graft harvesting and can result in patellar tendon rupture, patellar tendonitis, and patellar fractures (24).

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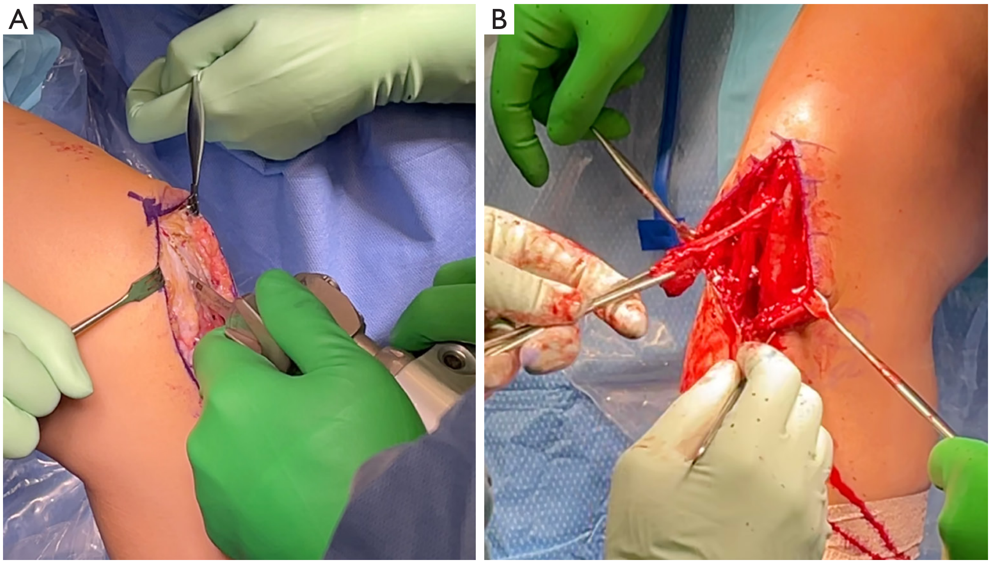

Figure 1 Harvest of BTB autograft. The senior author's preferred sizing is 10 mm tendon width, with 20 mm × 10 mm × 10 mm patellar and 25 mm × 10 mm × 10 mm tibial bone block. (A) Image depicting use of an oscillating saw to cut the patellar bone block. (B) Image depicting removal of BTB autograft. BTB, bone-patellar tendon-bone.

Figure 2 Image depicting hamstring autograft harvest. The senior author prefers to use an open graft harvester when using hamstring autograft.

In addition, BTB autograft has an increased risk of post-operative anterior knee pain that has been reported to occur in 5% to 55% of BTB ACLR (1,21). Therefore, the BTB autograft should be considered with care in sports such as wrestling in which the athlete is required to kneel, and in sports which require force across the anterior aspect of the knee for extended periods.

HS autograft

The HS autograft (*Figure 2*) offers several characteristics that make it advantageous for specific ACLR populations. Compared to BTB autograft, the HS autograft has a wider mid-substance surface area and lower overall rates of complications such as anterior knee pain, loss of knee extension strength, and range of motion (25,26). In addition, ACLR with HS autografts can be used for single-bundle or double-bundle ACLRs and has been associated with reliable clinical outcomes: studies have reported that 69% of patients return to pre-surgical levels following the HS autograft while 8% of patients experience residual knee laxity greater than 5 mm on KT-1000 testing (1). HS autografts are also the preferred choice for ACLR in skeletally immature athletes due to the decreased risk of local physis bone arrest, compared to BTB autograft (27).

Despite these advantages, HS autografts have been associated with increased healing and bone-graft integration times due to the absence of stabilizing bone plugs. Increased rates of infection with HS autografts have also been reported (12). HS ACLR may also result in decreased knee flexion torque in the post-operative period (1), and

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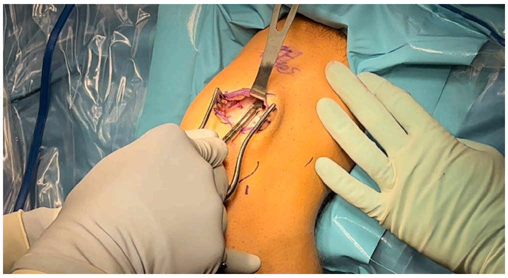

Figure 3 Image depicting quadriceps graft harvest using double scalpel handle.

thus may be an inferior choice for elite athletes who rely heavily on HS flexion such as sprinters, wrestlers, gymnasts, and long-distance runners. However, additional literature has suggested this effect generally resolves one year after surgery and HS strength recovery can be accelerated with biceps femoris training (28). Overall, the HS autograft remains an effective graft option for anatomic ACLR in elite athletes. When performed, the surgeon may consider a concomitant lateral extraarticular tenodesis (LET) which has been reported to result in decreased rates of graft failure when compared with isolated HS autograft ACLR (29), though there is speculation that this effect may be caused by the forced increase in recovery time resulting from concurrent LET that allows further maturation of the graft before it is significantly stressed.

Quadriceps tendon (QT) autograft

The QT autograft (*Figure 3*) has emerged as a potential graft option in recent years because it can be harvested with or without a bone block and as a full or partial thickness graft (30). The QT autograft has increased length, tensile strength and mid-substance cross-sectional area compared to the BTB autograft and therefore may be advantageous in elite athletes with a broad ACL footprint (12). In a study of 144 patients with primary ACLR, Han *et al.* reported comparable clinical outcomes for QT and BTB autografts (31). Notably, the authors found a significantly decreased incidence of post-operative anterior knee pain in the QT group (31). QT autograft also minimizes the risk of injuring the saphenous nerve, which remains a frequent complication of BTB graft harvesting (1). Furthermore, QT autograft has not been reported to have the increased risk of infection that accompanies HS autograft (32).

Comparing differences in knee stability, patient satisfaction and self-reported functional outcomes, a recent systematic review by Slone *et al.* found no significant differences when comparing QT versus HS and BTB autografts (33). Drawbacks to QT autografts include the risk of patellar fracture during graft harvesting, significant bleeding due to the profuse vascular supply of the QT, and rectus femoris retraction (12,33,34). The use of QT autograft in elite athletes remains largely uncharted due to the lack of trials with long-term follow up and the hesitancy surrounding potential loss of quadriceps function beyond that already associated with disuse during recovery. Additional high quality studies resulting in favorable clinical outcomes may encourage more surgeons to select the QT autograft for ACLR in elite athletes.

Allograft

The use of allografts for high-level athletes remains controversial. While the lack of donor site morbidity may be attractive in high-level athletes trying to return to play as efficiently as possible, the associated cost is higher reported rates of failure. Because of the reported increase in allograft rupture, especially in young patients, we do not recommend allografts as the first line choice for anatomic ACLR in elite athletes (12,35). A systematic review by Wasserstein *et al.* found a significantly increased pooled failure rate of 25% in ACLR with allograft compared to 9.6% with autograft (36). Additional evidence suggests that allograft usage in ACLR results in delayed return to sport versus autograft, potentially because autograft is more easily incorporated into host bone (37). In rare cases, allograft ACLR may be justified for elite athletes with a multiligament knee injury or significant compromise of autograft tissue, but autograft remains the preference of most surgeons (38).

Graft preparation and fixation

Graft preparation, tensioning, and fixation are essential considerations for successful ACLR, particularly in high-level athletes (see *Table 1*, surgical pearls and pitfalls). Failure to properly account for graft properties may result in significant postoperative knee laxity due to graft elongation and heightens the risk of ACLR failure. Debate exists in the literature regarding the proper graft pretensioning and preconditioning techniques that reproduce the biomechanics of the native ACL in various graft choices. This section will review principles behind

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Table 1 Surgical pearls & pitfalls for ACLR

Techniques	Pearls	Pitfalls
ACLR (all techniques)	Patient positioning to allow flexion up to 120° with stable varus/valgus maneuvering may be achieved by using a leg holder placed proximally and angled cephalad to slightly raise the knee	Failure to properly position patient prior to procedure may lead to inadequate visualization and/or angles for tunnels
	An accessory medial portal should be created prior to the femoral tunnel creation	Careful attention should be paid to not disrupt the meniscal root attachments during tunnel placement
	Preservation of some ACL tissue 'stumps' helps guide appropriate tunnel placements	Improper tunnel placement (femoral tunnel too vertical, too posterior; tibial tunnel too medial, lateral or posterior) will result in a non-anatomic and/or compromised reconstruction with higher risk of graft failure
	After graft positioning but before tensioning, cycling the knee may help remove slack and avoid impingement	Lack of physician coordination and involvement with physical therapy may result in improper timing of return to sport and increased levels of either failure or stiffness
	Use of dynamic force ACL brace in pre- and post-operative settings reduces strain on the injured or newly reconstructed ACL	
BTB autograft	The senior author's preferred sizing is 10 mm tendon width, with 20 mm × 10 mm × 10 mm patellar and 25 mm × 10 mm × 10 mm tibial bone block	Failure to create a sufficient incision may lead to accidental marking and harvesting of insufficiently sized bone blocks
	Arthroscopy portals may be created through the harvest site incision	Failure to create adequate cuts with the oscillating saw may result in fracture when retrieving the blocks via osteotome
	Care should be taken to dissect patellar paratenon from both sides of the graft	Failure to properly plan/mark the bone cuts may result in too large a block and increased risk of fracture, or too small a block and inadequate fixation/osseous integration
	A ruler and bovie may be used to mark oscillating saw cuts; a straight osteotome is used only for release of the bone plug	
	The graft is passed through the tibial tunnel and fixed in the femur first with a 7 mm × 20 mm titanium interference screw positioned superiorly on the tunnel (to maximize cortical contact of the graft)	
	Tibial fixation occurs with traction on the graft, with the knee in full extension, with a 9 mm × 20 mm titanium interference screw	
HS autograft	Use an open stripper during graft harvesting to ensure the distal gracilis tendon insertion remains intact	Failure to harvest a sufficiently long graft will result in a shortened final construct after folding that may be unsuitable for grafting
	Optimal final graft length after folding is between 6.0 and 6.5 cm	Increased rates of infection have been theorized to be caused by grafts hanging down from their distal insertions and contacting the lower areas of the leg, sterile field, and gown during harvesting
	Ideal tunnel size may be measured directly from the graft after preparation	
QT autograft	The tendon is often more lateral than anticipated, and thus positioning of the bone block cuts should be carefully aligned to create a straight graft	Marking the bone block too lateral will not align with the thickest part of the patella, which is medial
	Osteotomes should be used minimally (only for release of pre-cut bone) or not at all to reduce risk of patellar fracture	Avoid plunging through the patella too deeply to avoid damage to the femoral condylar surfaces
	Ensure the dissection goes deep enough into the second layer of the quadriceps tendon to avoid harvesting a graft that is too thin	
Allograft	Achilles allograft bone block should be sized to 10 mm × 20 mm, and soft-tissue graft shaping should retain uninterrupted fibers	Proper choice of patient population use is crucial to avoid failure in patients at high risk of graft rupture

A list of critical surgical and rehabilitation principles for optimizing success in various ACLR techniques. ACLR, anterior cruciate ligament reconstruction; ACL, anterior cruciate ligament; BTB, bone-patellar tendon-bone; HS, hamstring; QT, quadriceps tendon.

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Table 2 Comparison of restorative ACL techniques

Techniques	Advantages	Disadvantages	Questions
BTB autograft	Least amount of graft laxity	Donor site morbidity: risk of anterior knee pain	Can other techniques provide similar success without anterior knee pain?
	Low risk of failure/revision	Most technically challenging autograft technique	
	Double-sided bone plug	Not advisable for skeletally immature patients	
	Easily accessible		
	Consistently reproducible		
	Well-studied/good evidence		
HS autograft	Can be used in skeletally immature patients	Increased rates of graft laxity	How does the small increase in graft laxity differ in patient satisfaction between athletes and non-athletes?
	Easily accessible	Increased rates of infection	
		Donor site morbidity: risk of HS power loss	
QT autograft	Increased length, tensile strength	Donor site morbidity: risk of quadriceps retraction, increased loss of quad strength, increased bleeding	How does long-term follow up compare to other graft choices?
	Decreased anterior knee pain compared to BTB	Long-term evidence not robust	How much quad strength is compromised, and how does this affect athletes?
	Early study outcomes comparable to BTB		
Allograft	No donor-site morbidity	Increased rates of failure compared to autograft	Can allograft failure rate be remedied, so as to eliminate the need for donor-site morbidity?
	Usable in any age population	Longer time to incorporate into bone than autograft	
ACL repair	No donor-site morbidity	Higher failure rate compared to autograft, especially BTB, especially age <21 years	How does long-term data compare to ACLR?
	Restoration of native tissue	Long-term evidence not robust	Can ACL repair be improved to match or exceed outcomes of ACLR?
LET	Reduces rotational laxity	Additional invasive procedure	Is the risk-to-benefit ratio of LET warranted in elite athletes as an 'at-risk' population for graft failure?
	May decrease rates of graft failure when compared to isolated ACLR, especially in at-risk populations	Increased post-operative stiffness	

A comparison of selected autograft, allograft, repair, and augmentation techniques for the ACL. ACL, anterior cruciate ligament; BTB, bone-patellar tendon-bone; HS, hamstring; QT, quadriceps tendon; ACLR, anterior cruciate ligament reconstruction; LET, lateral extraarticular tenodesis.

pre- and peri-operative graft considerations for ACLR.

Optimal graft selection is a critical element of successful ACLR (*Table 2*). BTB and either single-bundle or double-bundle HS grafts are most frequently used for ACLR (39). Past studies have described the anatomic landscape of the ACL femoral and tibial attachments (*Figures 4,5*) (41,42). However, attention must also be given to the morphology of the ACL within the joint space. Graft selection which does not resemble the ACL midsubstance structure has been associated with increased risk of graft impingement and increases the risk of ACLR failure (*Figure 6*) (39,43). Using 3D magnetic resonance imaging

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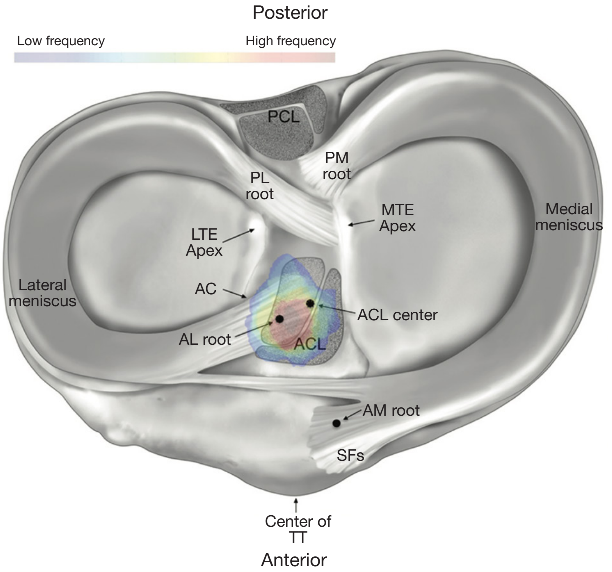

Figure 4 Illustration demonstrating the tibial attachment of the ACL and its proximity to the anterior root of the lateral meniscus. Used with kind permission of the *American Journal of Sports Medicine*, LaPrade CM *et al.* (40). PCL, posterior cruciate ligament; PL, posterolateral; PM, posteromedial; LTE, lateral tibial eminence; MTE, medial tibial eminence; AC, articular cartilage; AL, anterior lateral; AM, anterior medial; ACL, anterior cruciate ligament; SFs, supplemental fibers.

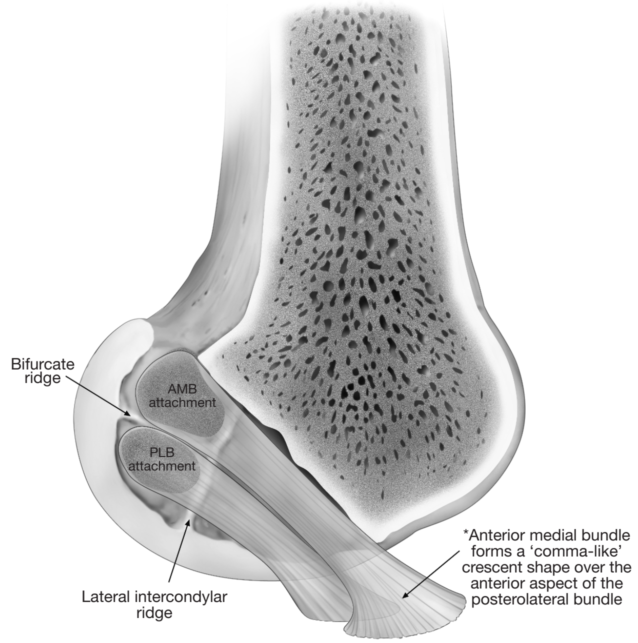

Figure 5 Illustration demonstrating the orientating of the femoral attachments of the two bundles of the anterior cruciate ligament and their proximity to bony landmarks. Used with kind permission of the *American Journal of Sports Medicine*, Ziegler CG *et al.* (41). AMB, anterior medial bundle; PLB, posterolateral bundle.

(MRI) reconstructions, Thein *et al.* reported that native ACLs are flatter in the middle with decreased cross-sectional area, and experience decreased impingement, compared to anatomically-oriented BTB ACL grafts (39). In addition, a cadaveric study by Triantafyllidi *et al.* reported that BTB, semitendinosus tendon, and gracilis tendon grafts have an undersized tibial insertion footprint, compared to the native ACL (43). Thicker ACL grafts have also been reported to disturb the native orientation of the PCL, particularly in the proximal femoral notch (39). Therefore, graft selection with a thin midsubstance, or careful shaping of the graft before implantation is recommended to avoid impingement and decrease the risk of ACLR failure.

Establishing an optimal preconditioning protocol based on graft type is necessary to produce an ACL graft that is biomechanically equivalent to the native ACL. An *in vitro* biomechanical study performed by Jaglowski *et al.* reported that increased-load cyclic and static graft preconditioning protocols resulted in significantly decreased postoperative graft elongation when compared to lower graft preconditioning loads (44). Specifically, use of a static load of 600 N for 20 seconds was found to have the least amount of displacement during simulated rehabilitation, and may be optimal for the clinical setting compared to a 600 N cyclical load. The standard load of 80 N was associated with significantly increased postoperative graft elongation compared to the 600 N static load. Despite this result, the 80 N load remains the standard of care in many institutions (44-46). Additional studies have found that graft preconditioning with a decreased load (~80 N) does not sufficiently precondition the graft and increases the risk for considerable postoperative graft elongation (47-49).

Return to sport following ACLR for high-level athletes requires graft fixation able to withstand enhanced loads on the knee joint during competition. Previous studies have reported the isolated use of interference screws for tibial fixation to be associated with graft slippage and dislodgement, resulting in low ultimate failure loads and the delay of postoperative rehabilitation (50,51). A porcine model biomechanical study by Walsh *et al.* reported that tibial ACL graft fixation with a combination of retrograde screw and suture button placement had significantly greater failure load than graft fixation with suture button or

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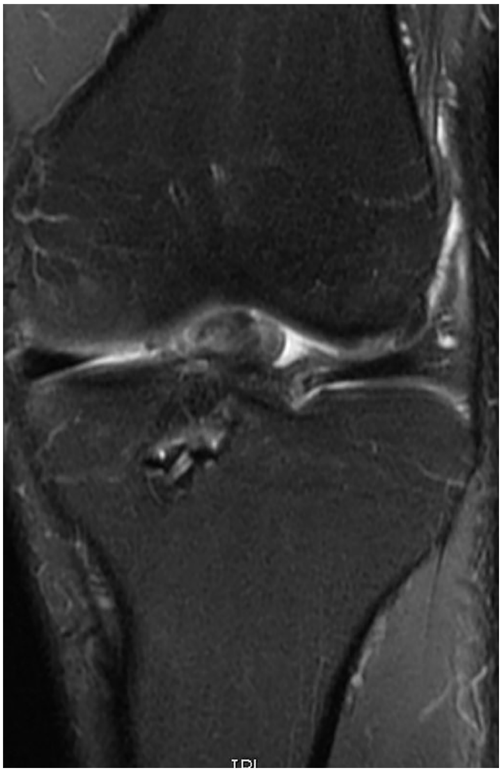

Figure 6 MRI demonstrating graft with impingement. MRI, magnetic resonance imaging.

retrograde screw alone (50). Furthermore, increased graft load strength with usage of both interference screw and a suture-post screw was reported in human patellar tendon grafts (52). Therefore, we assert that the most secure tibial fixation of soft tissue grafts can be achieved with hybrid fixation to maximize graft failure load and decrease the risk of ACLR failure for high-level athletes. For additional surgical pearls and pitfalls for ACLR (see *Table 1*).

Repair *vs.* reconstruction

While the idea of a primary repair for ACL injury is appealing, it has met with controversial results in various studies. A promising randomized controlled trial by Murray *et al.* found patient reported outcomes to be the same or better for bridge-enhanced ACL repair (BEAR) *vs.* ACLR with HS or BTB autograft (53). However, there are a number of concerning aspects of that study, the first being the control group they used was HS autograft, which the authors of this paper have advocated against being gold standard, especially for high-level athletes. Secondly, the 2-year failure rate for the repair was 14% which was 2.33× higher than the HS group (6%) and significantly higher than published failure rates in BTB population.

Another study proving the effectiveness of primary repair also showed similar subjective outcomes at two years between repair and reconstruction in a randomized controlled trial, but also reported greater necessity of additional surgical procedures in two years of follow up for the repair group (54). Of note, both of these studies used predominantly HS autografts (two patients total had BTB autografts), and it is worth noting that return to higher activity—especially elite level athletics—may differ between BTB autograft and a choice with donor-site morbidity associated with decrease in function, like HS autografts.

Age is another factor to consider regarding ideal candidates for ACL repair. DiFelice reported on 113 patients undergoing primary repair for proximal tears and noted patients under 21 years of age had a failure rate of 37% compared with 4.2% in patients aged 22–35 and 3.5% in those >35 (55). This would suggest repair is a poor option in younger high-level athletes and perhaps athletes in general given athletes in the 21–35 years old age range are likely much more active and high demand than the average patient in the same age group. Treatment of failed repairs is a topic that similarly has a dearth of current literature, however, early reports suggest that surgical management of a failed ACL repair may be notably more complex than a primary ACLR, with some studies reporting 60% of those patients requiring 2-stage ACLR (56). Finally, a review of the subject by Gee *et al.* rightly pointed out that although short-term outcomes may show promise in carefully considered cohorts, the medium- and long-term outcomes for ACL repair simply do not have enough evidence to support their recommendation at this time (especially in younger patients and athletes) due to higher failure rates of repair (57).

Lateral extra-articular augmentation

Augmentation of ACLR is a topic that continues to be debated. Biomechanical analyses of these reconstructive techniques has demonstrated superior ability to limit internal rotation compared with ACLR alone, and has even demonstrated mild overconstraint in regards to rotation compared with a native ACL state (58,59). Clinical studies have demonstrated similar results to the biomechanic literature. A randomized controlled trial by Getgood *et al.* found LET augmentation of single-bundle HS tendon

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ACLR resulted in statistically and clinically significant reductions in graft rupture and persistent rotational laxity (29). A recent systematic review by Na *et al.* assessed the functional outcomes, stability and complications between patients undergoing isolated ACLR and ACLR augmented with anterolateral extra-articular procedures (AEAP) including anterolateral ligament reconstruction and LET (60). They found that improved pivot shift grades and graft failure rates with AEAP compared with isolated ACLR. It should be noted that higher rates of stiffness were also found in the group undergoing ACLR + LET, suggesting that need for augmentation should be considered and weighed against the risk of additional post-operative stiffness.

Given the notable ability to stabilize and even overconstrain the knee, augmented procedures have gained popularity in at-risk patient populations (61,62). These high-risk populations have traditionally included; adolescent patients (63), revision ACLR (64,65), high grade pivot shift (66), increased posterior slope (67), soft tissue ACLR grafts (29), and knee hyperextension and generalized laxity (63,68). Another population which merits consideration is high-level athletes. Elite athletes have high rates both of primary ACL injury and re-rupture (69). Given these risk factors there has been recent interest in outcomes of augmented procedures in athletes. Borque *et al.* assessed 455 elite athletes undergoing ACLR or ACLR with LET and found that addition of an LET procedure reduced the rate of re-rupture by 2.8 times (70). More data is needed to evaluate routine use of augmented procedures in athletes who do not possess other high-risk qualities. However, participation in high-level athletics is clearly a risk factor for failure and therefore should factor in to the algorithm of when to use augmented techniques.

Future directions

To conclusively determine optimal graft choice, more high quality long-term comparative studies are required to determine ultimate longevity for different graft choices, and especially for QT autograft, and ACL repair, which we recommend be compared to multiple graft types including BTB autograft. In addition, large randomized, controlled trials may provide high levels of evidence for graft choice, but are difficult to set up. This may be especially useful it determining the utility of augmentation techniques such as LET. Further improvements in recovery for all graft types may also be seen through use of evidence-based post-operative rehabilitation, biologics, or other yet-undiscovered techniques. We strongly advocate attention to post-operative rehabilitation in particular as an under-appreciated aspect of optimal ACLR which merits further high-quality studies.

Conclusions

It is the preference of the corresponding author to use BTB autograft in all patients without a contraindication. It has been our experience that high-level athletes often prefer the trade-off of potential increase in anterior knee pain to the risk of losing performance from donor site morbidity such as in QT or HS autografts, or higher rates of failure and need for revision with use of allografts. However, HS autografts still have an important place in the setting of skeletally immature athletes. While QT autograft is a promising potential alternative to BTB autograft, the lack of high-quality evidence compared to the preponderance of literature evaluating BTB may make many practitioners wary of choosing this technique over one that is so much more highly studied. The increased rate of BTB incorporation into bone along with a high tensile strength and stiffness allow for less risk of failure during rehabilitation and graft maturation, particularly in high-level athletes who may be pressured to push themselves to perform sooner than recommended. When compared to allograft, despite increased risk of pain, the BTB autograft does not have a risk for decreased strength or function, and also lacks the increased risk of failure associated with allografts. It is also easily accessible during surgery, and the technique is easily reproducible with consistency. For elite athletes desirous to return to sport, the BTB autograft is highly recommended, but optimal graft choice will be affected by further considerations including patient age, sport type, level of play, and primary *vs.* revision ACLR (*Table 2*).

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All clinical procedures described in this study were performed in accordance with the ethical standards of the institutional and/or national research committee(s) and with the Helsinki Declaration (as revised in 2013). Written informed consent was obtained from the patients for the publication of this article and accompanying images.

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