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REVIEW

Optimal Graft Choice in Athletic Patients with Anterior Cruciate Ligament Injuries: Review and Clinical Insights

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Abstract: Anterior cruciate ligament (ACL) rupture is a common sporting-related knee injury with a potentially detrimental impact on the athlete's career, yet there is no formal consensus on the optimal graft choice for reconstructing the ruptured ACL in this specific population. Options for reconstruction include autograft, allograft, and artificial grafts. However, each has associated failure risk and donor site morbidity. Our operational definition of the athlete is a skeletally mature individual participating in high level activity with the expectation to return to pre-injury level of activity. The athlete has unique injury characteristics, post-operative expectations, and graft demands that differ to the general population. Long-term outcomes are of particular importance given on-going mechanical demands on the reconstructed knee. Therefore, the purpose of this review is to consolidate current literature on the various ACL reconstruction graft options, with a focus on the optimal graft for returning the athlete to activity with the lowest rate of re-injury.

Keywords: anterior cruciate ligament, reconstruction, athlete, graft choice, graft failure, return to activity

Introduction

The anterior cruciate ligament (ACL) is the primary restraint to anterior tibial translation and contributes to tibial rotational stability. Rupture of the ACL commonly occurs during sporting activity involving either a non-contact or pivoting mechanism. A higher incidence is observed in the young athlete population, with surgical reconstruction often performed to restore structural stability to the knee and facilitate return to sport. Reconstructing the ACL-deficient knee may also reduce the risk of long-term complications due to instability, such as injury to the menisci and cartilage.[1,2] Additionally, reconstruction has been shown to be economically advantageous with an increase in quality-of-life compared to rehabilitation and non-operative management.[3,4]

The ideal graft for reconstruction of the athlete's ACL will recreate the complex anatomical and biomechanical properties of the native ligament. An adequate graft length of over 7 cm with a mid-substance diameter between 10–11 mm contributes to the mechanical properties that allow the graft to withstand the tensile load, stiffness, and strain of a native ACL with minimal structural graft-related complications.[5–8] As this surgical technique has evolved over decades, a number of different grafts have been used by surgeons around the world. Each graft has unique features, advantages, and disadvantages, and ultimately graft choice is individualized depending on multiple factors. This includes surgeon experience and preference, tissue availability, patient activity level, occupation, comorbidities, prior surgery, extent of injury, and patient preference. Each contributes to the likelihood of post-operative success, which itself is a subjective measure unique to each patient. Aspects of surgical technique, such as graft fixation or femoral tunnel drilling method (transtibial or anteromedial portal) may also influence outcome; however, these have less influence on revision rates than graft selection and patient factors such as age.[9,10] Better understanding of graft choices and knowledge of updated evidence will facilitate decision-making around graft choice and ultimately improve outcomes, decrease morbidity, and lower revision rates.

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In the athletic population, the primary goal of ACL reconstruction (ACLR) is to return the athlete back to sport at the lowest rate of reinjury. Taking into consideration this goal, we aim to review the current literature on graft choices and outcomes and provide our recommendation on the ideal graft choice in primary ACLR in the athlete population.

Discussion

ACLR Graft Options

ACLR graft choices can be broadly categorised into autograft, allograft, and artificial grafts. The ideal graft should have similar properties to the native ligament, limit donor site morbidity, and allow for secure fixation and rapid incorporation.[8]

Autograft

Three autograft options are commonly used. The bone patella tendon bone (BPTB) autograft is classically harvested from the middle third of the patellar tendon. It produces a consistent graft diameter of around 10 mm and contains bone plugs from the patella and tibia at either end of the graft that facilitates bone-to-bone healing within the bony graft tunnel.[11,12] This reinforces fixation stability and is comparable to fracture healing, which is faster and stronger than soft tissue healing.[7] Typically, fixation is achieved using an interference screw which engages the bone plugs of the graft in the bony tunnel with compression, further facilitating graft healing.[13,14] Particular consideration should be taken in skeletally immature individuals as graft harvest and fixation methods could compromise physes and increase the risk of growth arrest.[8,12]

The hamstring tendon (HT) autograft is harvested from the semitendinosus and/or gracilis tendon to yield variable sizes and constructs.[15] In contrast to the BPTB autograft, the HT autograft is a soft tissue graft without bone plugs, therefore relying on soft tissue healing in bony tunnels, which may occur more slowly and is weaker compared to bone-to-bone healing.[11] Furthermore, the size of a HT graft ultimately depends on the size of the semitendinosus tendon, which varies between patients. There are a variety of different HT graft constructs which can involve creating as many as eight strands between the semitendinosus and gracilis tendons, and can produce a graft diameter varying from 6 mm to more than 10 mm. Literature supports greater biomechanical strength with larger grafts, but a downside of potential impingement during knee range of motion.[8] In contrast to the standardized interference fixation for BPTB, a variety of different fixation methods are used with the HT graft with no consensus on the optimal method between surgeons. The most common methods are interference screw, suspensory, or cross-pin fixation. Similarly, surgeons must choose whether to use an interference screw with a sheath or without, or a fixed or adjustable loop when using a suspensory fixation device. A concerning complication, thought to occur secondary to graft mobility within the tunnel, is development of a fibrous tissue layer around the graft which leads to tunnel enlargement. This is more common in the tibial tunnel, and can compromise graft integration and potentially complicate revision procedures due to the created bone defect.[11,16] Advantages include no donor-site compromise of the extensor mechanism which can impede early rehabilitation, polyvalence (variable composition and diameter) to meet specific reconstruction requirements, and reduced likelihood of causing growth arrest in the skeletally immature population.[15,17,18]

The quadriceps tendon (QT) autograft has recently increased in usage and popularity, with studies reporting comparable outcomes to HT autograft.[8,19] Different harvesting techniques have been described to obtain partial- to full-thickness grafts with or without a bone block.[20] The range of graft subtypes allow for different sizes and thicknesses and, therefore, varying biomechanical graft properties. For example, full-thickness QT harvested with bone block without retinaculum has been demonstrated to have equivalent load to failure compared to the BPTB autograft.[20] In addition, a variety of fixation methods have also been described. The versatility of the QT autograft in ACLR stems from its practicality in a variety of circumstances with differing tunnel sizes, tunnel positions, and navigating around previous grafts.[20] A consequent challenge is the applicability of outcomes of QT autografts as a cluster and the ability to determine specific outcome measures related to any QT autograft subtype. There is a lack of robust evidence describing outcomes from a "gold standard" QT autograft ACLR procedure, particularly in our target population.

Tunnel widening can occur with any graft type, but is more common with soft tissue grafts such as the hamstring autograft.[21] While not thought to affect short-term clinical outcomes, tunnel widening can make revision procedures more challenging and bone grafting may be required.[21]

Allograft

Allograft options for ACLR are numerous, with patella tendon, hamstring, tibialis posterior, tibialis anterior, and achilles tendon all described extensively in the literature.[3,22–25] Allograft has its main advantages of lack of donor site morbidity, better control over graft size, shorter operative time, and improved cosmesis.[3,26,27] Disadvantages include graft availability, cost, and, more significantly, infection risk and graft rejection.[3,26–28] Disease transmission remains a serious complication that has been largely eliminated with development of better donor screening and testing procedures and introduction of sterilization techniques.[7,26] However, a major drawback of sterilization techniques is the effect it has on the biomechanical properties of the allograft. All allografts have slower rates of incorporation compared to autograft, alongside a much higher failure rate of up to 25% in the active population.[8,29] Additionally, allograft is reported to have a lower return-to-sport rate compared to autograft (43% vs 75%).[30] Current evidence supports its use in specific circumstances such as multi-ligament knee reconstruction, inadequate autograft tissue, or in older, less active populations.

Artificial Graft

Artificial grafts were first reported as a reconstruction graft option in the 1980s, with the main attractions of lack of donor site morbidity, shorter surgical time, and reduced risk of disease transmission. And potentially an earlier return to sport.[27,31,32] However, early studies reported satisfactory short-term outcomes but mid-to-long term complications of immunological response, foreign-body synovitis, tunnel osteolysis, femoral and tibial fractures near tunnels, and delayed failure.[28,31,33,34] This resulted in a decline in use of artificial grafts, although there is a recent resurgence of interest with newer generation grafts that have yielded successful outcomes when used in specific circumstances, such as in an older population.[31,33,35,36]

Artificial graft is a broad term encompassing both synthetic and augmented grafts. They serve as scaffolds, stents, or prostheses in ACLR. Legnani et al[31] discuss the evolution of synthetic grafts and augments over the years, with the Ligament Advanced Reinforcement System™ (LARS™) being the most recent development. LARS, composed of polyethylene terephthalate, is designed to have better tissue ingrowth, particularly in intra-articular portions of the graft.[31,37] This addresses concerns from studies that have suggested failure of intra-articular artificial graft integration contributing to failure of early generation synthetic grafts.[38] However, causes of failure are multifactorial, ranging from impaired fibrovascular ingrowth secondary to surrounding foreign body reactions to mechanical factors such as fiber properties and tunnel position.[37]

Outcomes

There are multiple subjective and objective outcome measures to assess success of primary ACLR. Objective outcome measures frequently reported in the literature are graft failure, return to activity, and contralateral ACL injury. These factors are interlinked and have a combined 23% risk of secondary ACL injury in athletes younger than 25 years old.[39,40]

Graft Failure

Graft failure is the most common outcome analyzed in ACL research. Though it has varying definitions depending on study type, it is commonly defined as graft rupture or residual instability following ACLR. In the athletic population, this is one of the most important outcome measures, as one ACL rupture may threaten an athlete's career, but a second re-rupture may end a career.

The rate of graft failure reported in the literature ranges between 1.8–33%.[41–43] The most commonly reported risk factors for graft failure include graft type, age at surgery, and activity level.[27,44–46] Under 20 years old at time of surgery is the most commonly reported risk factor for graft failure.[9,41,44,46–53] For the athlete, the above three factors compound their risk of graft failure.

Autograft

An early meta-analysis by Freedman et al, consisting of studies between 1966 and 2000, reported a lower rate of graft failure with BPTB autograft compared to HT autograft.[9,54] Further registry studies and systematic reviews have

repeatedly highlighted lower rates of graft failure and revision surgery with BPTB autograft compared to HT and QT autografts in ACLR across subgroups of patient ages and follow-up timeframes.[10,55–57] A New Zealand (NZ) ACL Registry study reviewing 7,155 primary ACLR identified a higher revision rate with HT autograft compared to BPTB autograft (2.7% vs 1.3%, $p<0.001$).[10] Supporting this is a longitudinal study over 6 years illustrating a 2.1-times higher odds of graft failure with HT autograft compared to BPTB autograft ($p=0.004$).[58]

There are few adequately powered randomized controlled trials (RCTs) comparing outcomes following BTPB and HT autograft in primary ACLR. Early RCTs yielded comparative results between the two groups.[59–65] However, a prospective randomized study by Beynnon et al[66] illustrated superior objective results with BPTB autograft reconstruction compared to double-strand HT autograft at 3 years follow-up. Though not statistically significant, these findings are consistent with those by Maletis et al[67] which also identified a greater number of patients returning to preinjury activity levels following BPTB ACLR. Since, a double-blind RCT by Mohtadi et al,[46] consisting of 330 patients, compared 2 year outcomes between BPTB and HT autograft. The study reported a significantly lower proportion of traumatic reinjuries in the BPTB group (3 of 110) compared to the HT autograft group (7 of 110).[46]

Comparative data on QT grafts is limited and conflicting; however, studies report a failure rate of 2.2–4.8%, depending on the size of the study and duration of follow-up.[68,69] Runer et al[45] performed a prospective study of 875 patients undergoing ACLR and reported a 3-times higher risk of revision surgery when using a HT autograft compared to a QT autograft (OR=2.7, $p=0.007$). Furthermore, in high activity patients with a pre-injury Tegner score of ≥7, the revision rate was 11.1% in the HT autograft group compared to 5% in the QT autograft group ($p=0.01$).[45] Interestingly, the HT autograft cohort had significantly higher ipsilateral graft ruptures than contralateral ACL injuries (4.9% vs 2.3%), with this difference being more marked in individuals with higher activity levels (11.1% vs 4.2%).[45] In contrast, a Danish registry study illustrated higher graft failure (revision rate) for ACLR with QT compared to HT and BPTB (4.7 vs 2.3 vs 1.5%).[70] However, this study is limited by a lack of specificity on QT graft characteristics (ie, size, bone block use, fixation technique) and, therefore, applicability of its findings is limited. A prospective cohort study consisting of 48 patients (27 BPTB and 21 QT autograft) reported the highest rate of QT graft failure at 4.8% compared to 3.7%.[69] The main criticism is the small study sample size. Comparatively, the largest cohort study of 198 QT autograft compared to 30 BPTB autografts yielded graft failure rates of 2.0% and 3.3%, respectively.[71]

Current evidence suggests BPTB autograft for ACLR in the athletic population has a failure rate significantly lower than all other graft options.[9,10,46,54–58,66,67,69,70]

Allograft

Allografts have a consistently higher failure rate compared to autografts at all stages of follow-up, with up to triple the failure rate of autograft quoted by Bottoni et al.[3] Allograft failure is related to structural characteristics of the graft, sterilization techniques, and donor characteristics. Structurally, single-strand allografts have higher rates of graft failure compared to multistrand allografts.[22] Infection rates are higher with unsterilized and/or aseptically processed grafts. Viral and bacterial transmission risk remains low but has a high detrimental impact and is associated with non-irradiated allografts. Gamma radiation can be used to address infection risk; however, it has a higher graft failure rate compared to autograft and fresh frozen allograft.[25,26] Furthermore, donor characteristics influence graft failure rates with increased risk of failure of grafts from female donors over 50 years old.[22]

Allograft sterilization techniques alter the mechanical properties of allografts and are broadly categorized into radiation (gamma, electron beam, x-ray) or ethylene oxide. The extent of alteration to graft mechanical properties is dependent on irradiation dose exposure.[25] Doses greater than 2.5 kilogray (kGy) have been shown to decrease allograft tension and, therefore, result in greater post-operative laxity and predispose to failure.[25] Farago et al[26] reviewed articles over 29 years assessing the impact of various sterilization techniques on objective tendon mechanics (ie, failure load/ultimate strength and Young's modulus of elasticity). Findings from the review support freezing followed by gamma radiation or electron beam at 14.8–28.5 kGy as the sterilization technique with the greatest biomechanical preservation.[26] However, allograft failure is not attributable to sterilization techniques alone, as rates of allograft failure remain higher when comparing fresh-frozen allografts with autografts.[26]

In the young active population, allograft reconstruction is a risk factor for failure compared to autograft.[3,27,53,72–75] A systematic review by Hayback et al[73] suggested the odds of ACL graft rupture decreases with every yearly increase in patient age for a study population with a minimum mean age of 18 years. Allograft use has been shown to be an independent risk factor for graft failure and the need for any subsequent surgery, with the risk of repeat ACL injury being 5.2-times greater for an allograft compared to a BPTB autograft within the first 2 years of reconstruction surgery.[53]

Given the above risk-benefits, allograft is not recommended as a first option graft choice in isolated primary ACLR in the athletic population. They may be beneficial in certain circumstances such as for older patients, in ACL revision surgery, or cases of multi-ligamentous reconstruction.[31]

Artificial Graft

Multiple cohort studies have yielded positive short- to mid-term outcomes of the LARS^{TM} artificial graft subtype in ACLR.[32,76] However, there is limited evidence supporting favorable long-term outcomes of artificial grafts, even if isolated to LARS^{TM}. The large majority of studies are composed of small study populations, as expected with the infrequent use of synthetic grafts in primary ACLR. A retrospective study of 18 patients over 10 years by Tiefenboeck et al[77] reported a 27.8% artificial graft re-rupture rate. Similarly, Tulloch et al[38] published a 33.3% mechanical failure rate in artificial graft ACLR in a cohort of 55 patients over a median timeframe of 7.8 years.

An earlier study by Pan et al[33] compared mid-term outcomes between BTPB autograft and LARS^{TM} in a cohort of 62 patients undergoing primary ACLR. Findings from the study did not yield statistically significant differences in functional outcomes.[33] However, demographic characteristics of the study population are not entirely applicable to that of our athlete population, with a mean age of 34 in the BPTB autograft group and 36 in the LARS^{TM} group, and pre-operative Tegner scores consistent with recreational sport participation only.[33] A more recent systematic review of 748 studies by Fan et al[28] comparing BPTB autograft with synthetic and augmented graft reconstruction confirmed more favorable objective outcomes with BPTB autograft (OR=0.49; 95% CI=0.28–0.86).

Contralateral ACL Injury

Contralateral ACL injury is a major complication that is as impactful as an ipsilateral graft rupture for the young athlete following primary ACL reconstruction. It is associated with reduced function, quality-of-life, and likelihood of return to pre-injury activity.[78] Interestingly, some studies have reported that the risk of contralateral ACL injury may be higher than the risk of ipsilateral re-rupture following primary ACLR.[42,79,80]

Risk factors for contralateral ACL injury include younger age, sex, graft selection, and level of sport played.[52,81] Registry-based studies have consistently reported age at time of index ACLR as a statistically significant risk factor for contralateral injuries at all follow-up timeframes.[41,42,47,49,53,82–85] Furthermore, returning to a high level of activity post-reconstruction is a risk factor for contralateral ACL injury.[83] In a study of 2,488 primary ACLR from the MOON cohort, Kaeding et al[53] reported that the odds of a contralateral ACL tear increased by 0.12 for every increased point on the Marx activity score.

Leys et al[86] performed a randomized controlled trial comparing BPTB and HT autograft in 90 patients over 15 years and reported a 2.6-times higher odds of contralateral ACL rupture with BTPB. Similar findings have been reported by ACL registry studies.[10,42] In 17,436 ACL reconstructions recorded in the Kaiser Permanente Registry, a 1.3-times higher risk of contralateral ACL reconstruction was reported in patients with a BPTB autograft compared to a HT autograft.[42] In a NZ ACL Registry study of 7,155 patients, those in the BPTB group had 1.9-times higher risk of contralateral ACL reconstruction compared with the HT group (adjusted HR=1.91; 95% CI=1.15–3.16, p=0.012).[10]

In contrast, a 755 patient case series with 15-year follow-up by Bourke et al[79] showed no significant difference in contralateral ACL rupture between the BPTB and HT autograft groups (hazard ratio [HR]=1.5; 95% CI=1.0–2.2). Additionally, a randomized controlled trial of 330 patients with a minimum 2 year follow-up by Mohtadi et al[46] showed no difference in the rate of contralateral injury between graft types.

It is unclear why patients with a BPTB autograft have a higher risk of contralateral injury compared to patients with a HT autograft. One explanation is that patients with a BPTB autograft are more able to return to sport and do so earlier

and at a higher level, which consequently makes the contralateral knee susceptible to injury.[87] Other possible reasons may relate to biochemical changes or altered neuromuscular function following ACLR.

Return to Activity

In young active patients, the risk of reconstruction failure increases with higher activity levels.[1] A variety of different methods are used to define return to activity. Return to activity may involve a patient returning to casual, amateur, or competitive level of sport, or analyzing scores calculated from an activity questionnaire such as the Marx Activity Questionnaire or the Tegner Activity Scale. In a meta-analysis of 48 studies performed by Ardern et al[88] comprising 5,770 participants, an 82% return to participation, 63% return to pre-injury level, and 44% return to competitive sport at final follow-up (mean time 41.5 months) were reported.

The majority of studies compare return to activity rates with BPTB and HT autografts since they are the most common autografts used in ACLR for the athlete. Isolated meta-analysis of four RCTs comparing return to preinjury level of sport following BPTB and HT autograft for ACLR showed no difference (OR=1.02, 95% CI=0.7–1.5, p=0.92).[89] However, the majority of publications favor BPTB autograft when return to activity is the focused outcome.[87,90,91] In total, 7,556 patients from 69 studies were systematically reviewed by Ardern et al[89] to illustrate ACLR with BPTB was favored over HT autograft in return to pre-injury level of sport rates (OR=1.2). Supporting this is an updated systematic review of 20 articles, inclusive of 2,348 athletes by DeFazio et al,[91] which identified an 81% overall return to sport rate with BPTB autograft compared to 70.6% with HT autograft.

A common limitation when comparing return to activity between BPTB and HT autografts is the effect of surgeon preference and the possible selection bias. Some surgeons may prefer to use a BPTB autograft in "higher risk" patients such as individuals participating in competitive sport. Subsequently, this may introduce bias into these studies as expectations of "return to activity" varies and is more challenging in professional athletes when compared to an amateur or casual athlete returning to sport.

Some clinicians believe that a higher rate of contralateral ACL injury following primary ACLR with a BPTB autograft is a marker of success of the BPTB autograft, as it demonstrates that the patient had returned to sport prior to their reinjury, which is the goal of the original procedure. A study from the NZ ACL Registry supports this theory by only analyzing high activity patients with a pre-injury Marx score of 13, so that the patients in both graft type groups were of equal activity levels.[87] Subsequently, this study found that BPTB patients had higher odds of returning to activity compared to HT patients. Additionally, the study identified a higher proportion of individuals with BPTB autograft were performing at their preinjury activity levels (Marx score ≥13) compared to HT autograft at 2 years (23.3% vs 13.3%, respectively; p<0.001).[87] Cohort studies have reported similar findings of higher return to sport rate in BPTB compared to HT autografts.[40,90]

Donor Site Morbidity

Donor site morbidity is a significant concern, particularly when considering BPTB autograft in ALCR. Kartus et al[92] report 40–60% of patients report various donor-site problems following BPTB autograft use in ACLR. The most common symptom is anterior knee and/or kneeling pain.[8,92] Other serious, but rarer complications such as patella fracture and patella tendon rupture may also occur.[7,8] Another commonly used measures of post-operative symptomology is the Knee Injury and Osteoarthritis Outcome Score (KOOS). A RCT by Lind et al[93] of 99 adults illustrated that, at 2 years follow-up, 50% of HT autograft recipients compared to 27% of QT autograft recipients had donor site symptoms as assessed using KOOS.

Anterior and Kneeling Knee Pain

Average incidence of anterior knee pain with autograft ACLR is up to 21.5%.[18] There is a higher incidence of anterior knee pain and kneeling pain following ACLR using BPTB compared to all other autografts.[7,12,18,54,92,94,95] This is consistently proven in the literature, including a recent meta-analysis of 685 patients across seven studies which identified 35.7% of the BPTB ACLR population to have anterior knee pain compared to 5.7% of QT autograft recipients.[18] Furthermore, 70.8% of 100 patients in a retrospective non-randomized study evaluating donor site morbidity

following BPTB autograft ACLR had kneeling pain.[96] Symptomology can occur anywhere along the extensor mechanism and is likely to be related to graft choice and its harvesting method.[7,8]

A prospective study by Kartus et al[97] aimed to identify donor site-related problems and compared post-operative anterior knee sensitivity following two different BPTB graft harvesting techniques. The study suggested a correlation between anterior knee sensitivity and intraoperative injury of the infrapatellar branches of the saphenous nerve.[97] This nerve travels along the inferior medial aspect of the knee joint.[7] Thus, given its location, it is especially vulnerable to injury when harvesting the central third of the patellar tendon or when hamstring tendons are harvested through a medial incision.[98] This is further supported by literature highlighting anterior knee sensitivity and difficulty kneeling after incisions in the prepatellar area for various surgical procedures ranging from arthroscopic access to midline incisions for tibial nailing.[97] Therefore, it is important to consider the suitability and risk-benefit of a BPTB autograft in individuals whose lifestyle would be impacted by this.

Anterior knee pain may be associated with functional flexion and/or extension deficits in the postoperative period and, likewise, restoration of full extension compared with uninjured side after ACLR is essential to avoid post-operative discomfort in the anterior knee.[92] In some studies, the two are shown to have a statistically significant risk association.[94,98] Pain has been shown to occur 5-times more than in the absence of a deficit.[94,98,99] This may have consequential functional limitations and, therefore, result in impairment of the athlete with higher functional demands of the extensor mechanism of the knee.

Patella-Related Complications

Though rare, patella tendon ruptures and fractures of the patella or proximal tibia in the donor knee are associated with medial-third BPTB autograft use in ACLR.[100] If undiagnosed or inadequately managed, these disruptions to the extensor mechanism can have devastating functional impact.

Patella Fracture

The reported incidence of patella fracture in the donor knee following BPTB autograft harvest in ACLR varies between 0–2%, with no reports of association with other graft types.[101]

A literature review by Tay et al[101] of five case reports and eight case series, reports a cumulative 31 patella fractures following ACLR with BPTB autograft. The majority of these were sustained by indirect injuries and mostly stellate in configuration.[101,102] The average time to injury was 11 weeks, though it can be as short as 24 days.[101,102] The incidence of patella fractures suggests potentially altered distribution of forces acting on the iatrogenically weakened patella after graft harvest, therefore, placing it at increased risk of injury even at usual strain and contact stresses of normal activities such as stair climbing.[101] Management of these complications was governed by displacement.[101,102] Though complications extend rehabilitation, at full recovery, there was no significant difference in functional outcome between ACLR procedures complicated by patellar fracture.[101–103]

Patella Tendon Rupture

Patella tendon rupture is rare, with a reported incidence of between 0.2–1.3% after BPTB harvest.[54,96,100,102,104–108] This may not be a complication directly associated with BTPB autograft harvest alone, as earlier studies have reported this complication with other reconstructive grafts, including allograft and earlier-generation synthetic grafts.[107,109] However, occurrences with alternate grafts has not been described in recent literature.

Patella tendon rupture usually occurs secondary to trauma such as a fall, accompanied by either a forced hyperflexion injury or a forceful quadriceps contraction.[100,107,108] Current literature reports varying timing of occurrence following ACLR and patellar tendon rupture from days to years, with the majority occurring within the first year from surgery.[100,103,107,108,110] The concern regarding patellar tendon rupture in a BPTB harvested knee is the technical challenge of repair and early loss of flexion.[106,111]

A series of 13 cases of patella tendon rupture in the donor knee, from a database of 5,364 ACLR using BPTB autograft, identified varying tendon rupture sites differing from the commonly observed proximal-only tear pattern in unharvested patellar tendons.[111] The majority of post-reconstruction patellar tendon ruptures occurred from the patellar

origin medially extending to the tibial attachment laterally in a Z-shaped pattern.[111] In all cases, the donor site tendon defect was closed with running No. 0 Vicryl and the bone plug harvest defects in the patella and tibia were bone grafted with bone shavings from drilling of the femoral and tibial tunnels.[111] All cases recovered with positive long-term objective and subjective outcomes following patellar tendon repair and intensive rehabilitation.[111]

Range of Motion and Strength

A meta-analysis by Zhao et al[57] evaluated donor site morbidity following HT and BPTB ACLR. They identified a significant difference, favoring HT, with regard to loss in knee extension range (16.2% vs 10.2% for BPTB vs HT, respectively, OR=1.67).[57] However, a 15-year follow-up of a RCT by Webster et al[112] noted that early increased extension deficit following BPTB ACLR was no longer present at 15 years. There are yet to be additional long-term studies to challenge the findings by Webster et al.

Muscle strength of the reconstructed knee remains similar following ACLR with either BPTB and HT autograft, as illustrated in a RCT by Beard et al.[62] However, findings from a cross-sectional study highlight muscular weakness in the lower limb which has had a quadriceps tendon harvest compared to a contralateral undisturbed limb by 15% in men and 30% in women.[20] This is supported by Lind et al.[93]

Donor site morbidity is a major factor contributing to hesitancy around use of BPTB autograft in ACLR. It has the potential to have significant post-operative consequences on specific populations, particularly individuals whose occupation or sporting activities involve kneeling. Fortunately, patella-related complications are rare and long-term functional outcomes are statistically indifferent following management of these complications. Balancing objective outcomes with donor site morbidity, there is robust evidence supporting use of BPTB autograft in the vast majority of the athletic population.

Lateral Extra-Articular Procedures

Adjuvant lateral extra-articular procedures (LEAPs), including lateral extra-articular tenodesis (LET) and anterolateral ligament reconstruction (ALL), are increasingly performed with ACLR to provide additional rotational stability and, therefore, reduce the risk of graft failure in high risk patients, such as the athlete.[113–116]

A meta-analysis of 1,010 patients from six randomized controlled trials by Mao et al[114] illustrated a lower risk of graft failure in those who had ACLR and LET compared to those who had isolated ACLR. Of significance is the STABILITY study by Getgood et al.[117] This is the largest randomized multicenter study to date, looking at ACLR clinical failure between two ACLR groups – single-bundle hamstring tendon autograft without LET and with LET – in individuals between 14–25 years old. Recent data of 2-year outcomes illustrate statistically significant differences, with lower rates of clinical graft failure in the group receiving concurrent LET procedure (120 of 298 in the ACLR group compared to 72 of 291 in the ACLR+LET group, RRR=0.38; 95% CI=0.21–0.52; $p<0.0001$).[117] Return to level of sport activity (Marx score) remains similar in both study groups.[117]

Similarly, the SANTI study group compared outcomes between isolated autograft ACLR to combined autograft ACLR with ALL procedure.[118] Findings from this prospective cohort study of 270 patients showed statistically better ACL graft survivorship in the group who underwent ACLR with ALL (96.5% vs 82.6%; $p=0.0027$). Additionally, at 108 months, those who had concurrent ALL with primary ACLR had at least 2.5-times reduced graft failure rates.[118]

There is increasing evidence supporting concurrent LEAPs in primary ACLR to reduce risk of graft failure, particularly in high risk population groups such as athletes. Current limitations in evidence include comparisons between specific autograft subtypes and concurrent LEAPs. This is a developing area which will drive significant change in management of primary ACLR in the coming years.

Conclusion

In the athlete undergoing ACLR, the primary aim of treatment is to enable the highest rate of return to sport at the lowest rate of reinjury. When considering this aim, literature clearly supports the use of autograft over allograft, and more specifically the use of a BPTB autograft in primary ACLR. QT grafts are a newer development compared to other autografts and evidence supporting their use in reconstruction of the athlete's ACL is presently limited. Although the HT autograft is more commonly used globally, the BPTB autograft has been consistently reported to have the lowest rate of

failure by both RCTs and national registry studies. Additionally, there is evidence that patients with a BPTB autograft are more likely to return to sport and at a higher level. However, this comes at the expense of greater donor site morbidity with BPTB autografts, including a higher incidence of anterior knee pain, kneeling difficulty, and rare, but severe complications such as patella tendon rupture and fracture.

Individualizing graft choice remains the most important when consulting the ACL-deficient athlete, and the athlete must balance their desire and aspiration to return to sport, risk of reinjury, and donor-site morbidity.

Disclosure

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