Graft Selection in Anterior Cruciate Ligament Reconstruction

Kenneth M. Lin, MD, Caroline Boyle, BS, Niv Marom, MD, and Robert G. Marx, MD

Abstract: Surgical reconstruction of the anterior cruciate ligament (ACL) is often indicated to restore functional stability and prevent early degeneration of the knee joint, as there is little biological healing capacity of the native ACL. Although a reconstructed ACL does not fully restore the original structure or biomechanics properties of the native ACL, the graft used for reconstruction must not only have structural and mechanical properties that closely resemble those of the native ligament, it must also have minimal antigenicity and enough biological potential to incorporate into host bone. There are several considerations in graft selection: autograft versus allograft, and soft tissue grafts versus grafts with bone plugs. Commonly used grafts include bone-patella tendon-bone, hamstring, and quadriceps; among allografts, options further include tibias anterior and posterior, Achilles, an peroneal tendons. Optimal graft selection is not only dependent on graft properties, but perhaps more importantly on patient characteristics and expectations. The purpose of this review is to summarize the relevant biological, biomechancial, and clinical data regarding various graft types and to provide a basic framework for graft selection in ACL reconstruction.

Key Words: anterior cruciate ligament reconstruction, autograft, allograft, bone patellar tendon bone, hamstrings, quadriceps

(*Sports Med Arthrosc Rev* 2020;28:41–48)

Rupture of the anterior cruciate ligament (ACL) is a frequent injury in the general population, with an incidence up to 75 per 100,000 person-years,[1] particularly in younger active individuals involved in cutting or contact sports. With increased early sports participation, incidence in the pediatric population is also rising.[2] It is known that there is little biological healing potential in the native ACL. Thus, surgical reconstruction of the ACL is often indicated to restore functional stability during athletic activity and prevent early degeneration of the knee joint.[3,4] Surgical reconstruction is performed using a variety of graft types, each with its own benefits and disadvantages. Despite the large volume of research and improvements in surgical technique, there is still considerable debate regarding the ideal graft choice for any particular patient.

Although a reconstructed ACL does not fully restore the original structure or biomechanical properties of the native ACL,[5] the graft used for reconstruction must not only have structural and mechanical properties that closely resemble those of the native ligament, it must also have minimal antigenicity and enough innate biological healing potential to adequately incorporate into the host bone. In selecting graft types, there are several considerations: autograft versus allograft, and soft tissue only grafts versus grafts with bone plugs. The commonly used autograft types are bone-patella tendon-bone (BTB), hamstring, quadriceps (with or without a patellar bone plug); among allografts, additional options include tibialis anterior and posterior, peroneal, and Achilles tendon. Optimal graft selection depends not only on graft properties, but more importantly on patient characteristics and expectations. It is essential for the surgeon to have a thorough understanding of the surgical techniques, the basic biology of graft-bone healing, and patient expectations regarding donor site morbidity, postoperative recovery and return to activity, and potential longer term outcomes.

AUTOGRAFTS

Autografts, in particular BTB and quadrupled hamstring (Fig. 1), have been most used for ACL reconstruction. Theoretically, from a biological healing perspective, autografts are preferred because they consist of viable autogenous tissue and avoid the risk of disease transmission, maximizing the speed and likelihood of complete biological integration at the graft-host junction. Within the autografts, major considerations are donor site morbidity, and graft-tunnel healing. Clinically, the most commonly used autografts are BTB and hamstring,[6–8] followed by quadriceps tendon.

Bone-Patellar Tendon-Bone Autograft

BTB autograft was the first graft used for ACL reconstruction.[9] The presence of bone plugs at both ends of the graft allow for retention of a native tendon-bone interface and thus graft-host integration via bone-to-bone healing. Creeping substitution at the bone-to-bone graft-tunnel interface creates a true bony junction, and is known to be stronger than soft tissue-bone healing that occurs through a fibrovascular scar.[10] In laboratory studies, complete graft integration has been shown to occur more rapidly with a bone-bone interface compared with tendon-bone.[11] Despite these findings, in the clinical setting, good graft incorporation can be achieved with all graft types (Fig. 2).

Biomechanically, BTB autograft has similar properties to the native ACL, with slightly higher ultimate tensile load, but a smaller cross-sectional area[10,12] (Table 1). In addition to the smaller cross-sectional area, the dimensions of the BTB graft are fixed and dependent on the patient's native anatomy; patella baja or alta will lead to a shorter or longer graft, respectively. Variations in this graft length can lead to technical challenges, specifically graft-tunnel mismatch. Another theoretical disadvantage to BTB grafts is aperture micromotion. Laboratory studies have shown that motion is greatest and healing is slowest at tunnel apertures.[14] Given

From the Sports Medicine and Shoulder Service, Hospital for Special Surgery, New York, NY.

Disclosure: R.G.M.: American Orthopaedic Society for Sports Medicine—Board or committee member; Demos Health-Publishing royalties, financial or material support; HSS Journal-Editorial or governing board; International Society of Arthroscopy, Knee Surgery, and Orthopaedic Sports Medicine-Board or committee member; Journal of Bone and Joint Surgery—American—Editorial or governing board; Mend-Stock or stock options; Springer-Publishing royalties, financial or material support. The remaining authors declare no conflict of interest.

Reprints: Niv Marom, MD, Hospital for Special Surgery, 535 East 70th St, New York, NY 10021.

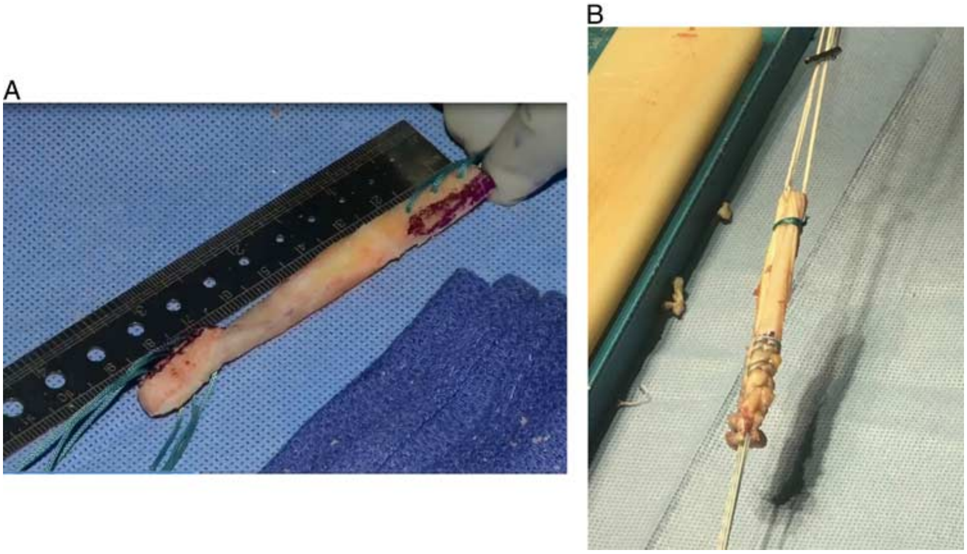

FIGURE 1. Intraoperative images of BTB (A) and hamstring (B) autografts after harvest and preparation. BTB indicates bone-patella tendon-bone. full color online

the BTB graft's fixed tendon length and decreased cross-sectional area, the mismatch in cross-sectional area at the tunnel aperture theoretically allows greater motion; intraoperatively this is often addressed by using aperture fixation. Nonetheless, despite the few theoretical biomechanical disadvantages, BTB grafts are known to lead to improved postoperative stability and decreased rates of early rerupture compared with other graft types.[15,16]

There are several clinical disadvantages of using BTB autograft. First is donor site morbidity, as BTB is harvested from the central third of the patellar tendon with bone blocks from the patella and tibia, through a larger incision than hamstring harvest. Anterior knee pain is more common after BTB harvest, with incidence reported up to 42%,[17] although this has not been shown to change functional scores, overall activity level, or return to same level of play.[15,17,18] A larger incision carries a theoretical increased risk for infection although this has not been shown in clinical studies, with reported infection rates ranging from 0.1% to 0.3%.[19] Intraoperative and postoperative patella fracture due to the disruption of the extensor mechanism has been reported as a rare complication.[20,21] Fractures occur after direct or indirect trauma or as a result of physiological forces applied on a mechanically weaker patella,[21] tend to be transverse, and after proper treatment do not change overall outcomes at midterm follow-up.[22] Proper harvesting technique and the use of bone graft to fill the patellar void after BTB harvest, may theoretically decrease postoperative fracture risk. Another rare complication that has been reported is patellar tendon rupture.[23] At long-term follow-

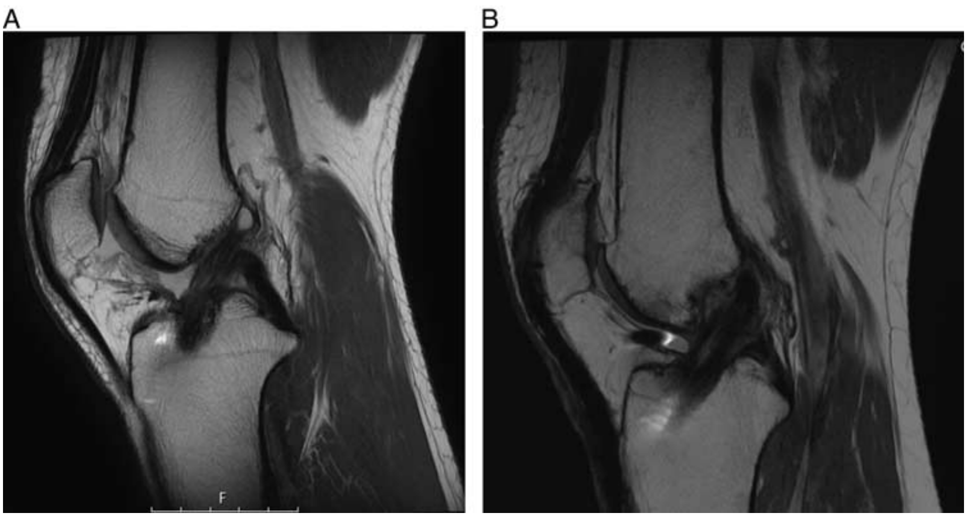

FIGURE 2. Postoperative sagittal proton density magnetic resonance images of healed ACL reconstruction after hamstring autograft (A), and quadriceps autograft (B). Grafts show intact fibers and good incorporation at the tunnel interface. ACL indicates anterior cruciate ligament.

TABLE 1. Biomechanical Properties of ACL Graft Options*

	Tensile Load (N)	Stiffness (N/mm)	Cross-sectional Area (mm²)
Native ACL	2160	242	44
Autograft			
Bone-patellar tendon-bone	2977	620	35
Semitendinosus tendon	1216	186	14.0
Gracilis tendon	838	170	7.6
Quadruple hamstring	4090	776	53
Quadriceps tendon	2352	463	62
Allograft			
Bone-patellar tendon-bone	1403	224	
Achilles	1189	743	105
Tibialis anterior	3012	343	

*Adopted from data by Noyes et al,[13] West and Harner,[10] and Mehran et al.[6]

ACL indicates anterior cruciate ligament.

up, it has been suggested, based on nonrandomized trials, that patients who have undergone BTB autografts may be at a slightly increased risk of radiographic evidence of osteoarthritic change at 15 to 20 years postoperative; however, the clinical significance of these findings is still unclear as functional scores and activity level remain high.[17,24]

Hamstring Autograft

Hamstring autograft is typically harvested through a small longitudinal incision over the medial proximal tibia. The insertions of the semitendinosus and gracilis are identified deep to the Sartorius fascia, and tendons are harvested by stripping off the muscle and detaching proximally. Because of the small incision size, no additional trauma to the extensor mechanism, and no bony disruption, donor site morbidity is much less with hamstring harvest than BTB harvest. Biologically, however, as a purely soft tissue graft, the absence of a bone plug necessitates tendon-bone healing and the generation of fibrovascular scar tissue rather than reconstitution of the native direct insertion with a fibrocartilage transition zone. In controlled laboratory studies, tendon-bone healing has been shown to be slower than bone-bone healing, with hamstring grafts showing inferior initial pullout strength to BTB, but no difference by 6 weeks in a canine model.[25] This longer period of initial graft integration may also be present in clinical practice, as large studies have shown greater rates of early re-rupture after ACL reconstruction with hamstring compared with BTB,[16,26,27] although many of these are midsubstance failures.

Biomechanically, a quadrupled hamstring graft achieves greater ultimate tensile load, stiffness, and cross-sectional area than both BTB autograft and the native ACL[6,10] (Table 1). Compared with BTB grafts, the likelihood of graft tunnel mismatch is less likely; however, hamstring autograft size may be limited by variability in native hamstring anatomy. It has been shown that there is increased risk of failure after ACL reconstruction with hamstring grafts of 8 mm and smaller in diameter.[28,29] Several recent large retrospective studies have modeled the relationship between increase in hamstring graft size and reduced risk of failure,[30,31] with Snaebjornsson et al[30] reporting a 0.85× lower likelihood of revision surgery with every 0.5 mm increase in hamstring autograft diameter, based on national registry data from Sweden. Graft size can be roughly predicted using the patient's height and preoperative MRI scan[28]; however, in the event of a small graft or technical problem during graft harvest, augmentation using allograft tendon can be performed. Inaddition, smaller hamstring grafts have been associated with particularly high failure rates in patients below 20 years of age.[28]

Aside from early failure and small graft diameter, there are several important postoperative considerations when using hamstring autograft. Hamstring weakness after tendon harvest is a concern, as it has been demonstrated that peak isokinetic torque is decreased after hamstring autograft compared with BTB autograft at 5 years after ACL reconstruction.[32] In light of this reported postoperative loss of hamstring strength, some authors recommend avoiding hamstring autograft in high-level athletes.[33] However, there also exist studies suggesting that there is no difference in postoperative knee flexion strength after hamstring harvest compared with BTB.[34] Further high-quality studies are required to fully elucidate the likelihood of postoperative hamstring weakness and the role of rehabilitation programs in its prevention.

Another concern with hamstring grafts is tunnel widening and its possible association with increased postoperative laxity. Radiographic tunnel widening has been reported, at a higher rate following hamstring than BTB autograft, in both short and intermediate-term follow-up, and in a systematic review of randomized trials.[6,35,36] The hypothesized mechanism is graft micromotion, which in animal models has been shown to be greatest at tunnel apertures and least at tunnel exits.[14] Fixation technique likely affects graft micromotion, as suspensory fixation is thought to lead to greater graft micromotion at the apertures, although this is yet to be shown in large studies. Tunnel widening is a concern because it may be associated with increased laxity postoperatively following ACL reconstruction with hamstring autograft. Although some studies have shown no difference in laxity,[8] several large studies and systematic reviews have shown increased likelihood of positive Lachman, pivot shift, and laxity on KT-1000 measurement.[15,37,38] Despite the increased objective laxity, there is no difference in patient-reported outcome scores (PROs), and the long-term effects on joint degeneration are unclear, as the use of hamstring autograft has been associated with decreased risk of osteoarthritis at long-term follow-up in 2 retrospective series.[17,24]

Comparison of Outcomes After BTB Versus Hamstring Autograft

Many studies have compared clinical outcomes and retear rates after BTB and hamstring autograft. Postoperative PROs are similar, with both grafts yielding high patient satisfaction and PRO scores.[15,17,24,39–42] In addition, the time to safely return to play has been shown to be similar between the 2 types of grafts.[42,43]

There are, however, several outcomes that differ after BTB and hamstring autograft. BTB is associated with greater stability on KT-1000 and pivot shift tests.[15,41] More importantly, BTB grafts have been shown in several separate cohorts to have lower retear rate than hamstring grafts, with up to a 2 to 4-fold higher retear risk with hamstring autograft.[8,16,26,27] This difference in retear rates is especially important for high-risk patients who are young and play cutting and pivoting sports and thus already have a high risk for retearing their graft. Nonetheless, despite the lower

Copyright © 2020 Wolters Kluwer Health, Inc. All rights reserved.

retear rate, BTB grafts are associated with greater anterior knee pain than hamstring autograft.[15,40] In addition, an increased risk of postoperative quadriceps weakness has been reported after BTB autograft harvest.[44]

There is limited long-term follow-up data in the literature, but there are 2 recent studies with 15- and 20-year follow-up that suggest that this increased risk of re-rupture persists after the immediate and intermediate postoperative period.[17,24] Thompson et al[24] reported an 18% and 10% failure rate, respectively at 20 years after hamstring and BTB autograft use. Interestingly, both long-term follow-up studies suggest increased incidence of radiographic osteoarthritis in the BTB group. The clinical significance of this finding is unclear, as despite the radiographic degenerative changes, all functional and PROs scores were similar between the 2 groups. Further long-term studies need to be conducted to determine the effect of graft choice on long-term knee health as there are many confounding factors that affect long-term outcome studies.

Quadriceps Autograft

Another autograft option, which has gained interest recently, is the quadriceps tendon.[45] Graft harvest is typically performed using a separate anterior superior incision over the distal quadriceps tendon, and the central third of the tendon is harvested. Depending on surgeon preference, a bone block from the superior patella may be harvested as well to maintain a native tendon-bone interface. Benefits to quadriceps autograft are consistently greater graft cross-sectional area, reduced risk of anterior knee pain and kneeling pain, and decreased risk of patellar fracture compared with BTB.[45–48]

There are several recent clinical comparative studies investigating outcomes after quadriceps tendon versus other autografts for ACL reconstruction. A prospective randomized study of 39 patients by Lund et al[46] found that compared with BTB autograft, at 1- and 2-year follow-up, there were no differences in outcome scores or laxity testing after quadriceps autograft, but there was a lower incidence of graft site pain and kneeling pain. A more recent, nonrandomized retrospective study of 90 patients at minimum 3 years postoperative by Cavaignac et al[49] compared outcomes after quadriceps versus hamstring autograft. Their results suggest similar to slightly improved outcome scores, improved stability on KT-1000 measurement, and greater likelihood of negative Lachman following quadriceps tendon autograft, with no difference in morbidity. A similar recent retrospective comparative study of quadriceps versus hamstring showed no difference in postoperative outcome scores, return to preinjury activity level, or morbidity.[50] Results from larger, ongoing clinical studies with more patients and longer follow-up will provide further insight into the benefits and risks of using quadriceps tendon in ACL reconstruction.

ALLOGRAFTS

Allografts are commonly used in ACL reconstruction, with reports of 22% to 42% of ACL reconstructions being performed with allografts in the United States.[51,52] Options include allograft BTB, quadrupled hamstring, quadriceps, Achilles, tibialis anterior and posterior, and peroneals. Anatomic origin of the allograft affects biomechanical properties, with greatest load to failure seen in looped tibialis anterior or posterior (Table 1), greatest stiffness in quadriceps, and lowest load to failure and stiffness in non-looped tibialis anteriorgrafts.[53,54]

Graft processing is an important consideration in selecting an allograft. Irradiation has been associated with higher rates of graft failure in numerous clinical studies. A dose-response relationship has been established with higher levels of gamma irradiation being associated with decreased load to failure.[55–57] Electron beam sterilization is thought to be less detrimental to the structural and biomechanical properties of allografts.[58,59] Aside from radiation, there are chemical sterilization techniques as well. Among these, peracetic acid, ethylene oxide, and supracritical CO_2 treatment have been shown to decrease stiffness and load to failure in various types of allograft.[53] In general, the less processed an allograft is, the more structurally and biomechanically stable it is; however, processing helps to decrease both disease transmission and the host's immune-inflammatory response to the graft. Transmission of viruses such as hepatitis B, hepatitis C, and HIV, is a rare but feared phenomenon, with an estimated risk of about 1 in 1,667,000.[6] Although true graft immune rejection has not been reported, fresh frozen allografts have been shown to be associated with a postoperative inflammatory synovitis possibly reflecting a latent immunologic response.[60]

Several other notable considerations for allografts are storage method and donor characteristics. Freezing at −80°C for > 30 days, > 3 freeze-thaw cycles, and treatment with various preservatives have all been shown to have negative effects on biomechanical properties.[53] Regarding donor characteristics, increased donor age has been shown to have a negative correlation with ultimate tensile strength and modulus of elasticity.[53,61] Although these allograft factors are likely un-modifiable for each individual case, the surgeon should become familiar with the local tissue bank's methods for acquisition, processing, and storage.

Autograft Versus Allograft

The clinical literature generally shows superior outcomes following ACL reconstruction with autograft compared with allograft, although good results have been reported with allograft as well. The many permutations of the allograft versus autograft comparison, given the different anatomic types and processing methods, make interpreting individual studies in the greater context of clinical practice somewhat difficult. Furthermore, in clinical studies, the different types of allografts are often grouped together into a single cohort, causing confounding from various graft-related factors discussed above. Nonetheless, there has been an abundance of recent literature focusing on outcomes after allograft versus autograft ACL reconstruction.

Several notable studies of ACL reconstruction using autograft BTB versus allograft BTB have shown superior outcomes in the autograft group. Krych et al[62] reported a 5-fold increase in risk of rerupture after BTB allograft compared with BTB autograft. When excluding irradiated and chemically processed grafts, they saw no difference in failure rate between BTB allograft and autograft; however, their meta-analysis/systematic review only included 6 studies. Kraeutler et al[63] reported similar results with an approximately 3-fold increase in risk of graft failure after BTB allograft compared with BTB autograft (12.7% vs. 4.3%). They also showed increased knee laxity, decreased single-leg hop test results, and lower subjective satisfaction after BTB allograft. Notably, however, patients in the

Copyright © 2020 Wolters Kluwer Health, Inc. All rights reserved.

allograft group had significantly less knee pain, and processing and irradiation of allografts was not differentiated.

With regard to graft processing, it is generally believed that sterilization techniques alter the biomechanical properties of a graft, and that the more processed a graft is, the worse it performs. Park et al[64] performed a systematic review of irradiated versus nonirradiated allografts at minimum 2-year follow-up, showing lower outcome scores, decreased stability to Lachman, pivot-shift, and KT-1000 testing, and increased risk of revision compared with nonirradiated allografts. Several other recent studies, including by Yao and colleagues and Tian et al[65] have shown similar results.

With greater failure rates and worsened biomechanical properties after use of irradiated grafts, some authors have suggested that nonirradiated allografts may have similar outcomes to autografts. Mariscalo et al[66] performed a retrospective study comparing BTB autografts and nonirradiated allografts, reporting no significant difference between the 2 groups in postoperative laxity, outcome scores, or failure rates. Most recently, Maletis et al[67] performed a large registry-based retrospective cohort study of 14,015 ACL reconstructions with BTB autograft, hamstring autograft and soft tissue allograft subcategorized based on processing and irradiation. Using an adjusted model for age, sex, and race, they found that BTB autograft had the lowest revision risk, followed by hamstring autograft [hazard ratio (HR), 1.51], allografts irradiated with <1.8 Mrad with chemical processing (HR, 2.19) and without chemical processing (HR, 2.31), and allografts irradiated with >1.8 Mrad with chemical processing (HR, 5.03) and without chemical processing (HR, 6.30). In their cohort, nonprocessed allografts and those irradiated with <1.8 Mrad had a similar risk of revision compared with hamstring autografts.

Caution must still be taken when applying these findings to patients in practice, as various patient factors must be considered in addition to graft type when discussing failure rate and long-term outcomes. Kaeding et al[68] reported, as part of the Multicenter Orthopaedic Outcomes Network trials, that although patients undergoing allograft ACL reconstruction had an overall 4× greater chance of graft rupture, they saw a notable impact from age, with a higher failure rate in all grafts in younger patients.

GRAFT SELECTION IN THE PEDIATRIC PATIENT

Given the increasing incidence of pediatric ACL tears,[2] ACL reconstruction in the skeletally immature population is becoming a growing area of interest. The main strategies for ACL reconstruction in the pediatric population, depending on the patient's skeletal maturity and surgeon preference, are transphyseal reconstruction, all-epiphyseal reconstruction using soft tissue graft and bone tunnels in the epiphysis, and physeal-sparing reconstruction using iliotibial (IT) band autograft without bone tunnels, also known as the modified Macintosh technique.[69] Trans-epiphyseal technique is similar to adult ACL reconstruction and is used in patients nearing skeletal maturity; however, oftentimes more vertical tunnels are preferred to leave a smaller footprint crossing the physis. In more immature patients, a completely physeal sparing approach can be used in which tunnels are entirely in the epiphysis; intraoperative 3D imaging or navigation can be used to aid in confirming tunnel placement. Only soft tissue grafts (not allografts) should be used for ACL reconstruction in pediatric patients with open physes.[70] The quadrupled hamstring graft is most common, although quadriceps tendon graft may be used. The patella tendon should not be harvested in pediatric patients with open physes to avoid damage to the tibial tubercle apophysis. Allografts are not indicated in pediatric patients in most cases, as allografts are known to have a higher failure risk.

Alternatively, the modified Macintosh procedure uses the native IT band, with its distal insertion onto Gerdy tubercle left intact, threaded into the notch in an "over the top position" and brought over the anterior tibial plateau between the tibial spines and under the intermeniscal ligament as the ACL graft.[71] Although the literature on ACL reconstruction in the skeletally immature patient is quite limited,[72] good outcomes have been reported. After IT band autograft physeal sparing ACL reconstruction, at 6-year postoperative, the failure rate has been reported to be 6.6% with excellent clinical outcomes and no limb length discrepancy or angular deformity.[73]

GENERAL ALGORITHM FOR GRAFT SELECTION IN ADULT PATIENTS

Despite the abundance of studies on ACL graft types, there is still no ideal graft, and there is no generally accepted algorithm for graft selection for a given patient. In the clinical setting, all graft factors discussed above must be considered, such as biomechanical properties, presence of a bone plug, donor site morbidity and graft availability (in places where allografts are not routinely used). Applying the literature on failure rate and clinical outcomes, several key clinical factors to emphasize are age, desired activity type and level, occupation, barriers to rehabilitation, and general expectations, as these factors affect failure rate, outcomes, and satisfaction. In the setting of revision ACL reconstruction or multiligamentous reconstruction, previous tunnels, grafts, and implants, and availability of autograft donor sites must be considered.

In general, for primary ACL reconstruction, adult patients can be divided into 3 main categories: elite athletes and young highly active patients, recreational athletes and active individuals, and older or less active patients.

Overall, in the setting of a primary isolated ACL reconstruction, the preferred graft of choice for consideration in the youngest, most active group is BTB autograft, although with the expanding literature, quadriceps tendon autograft may become an increasingly viable option in this population as well. Given that hamstring autograft and allograft have both shown higher failure rates and increased postoperative laxity, these choices are less ideal although they are still frequently used, especially in the revision or multiligamentous setting or if the patient has pre-existing anterior knee pain, or is required to kneel frequently due to occupation.

For the patients in the middle category, who are moderately active but not necessarily elite athletes, and are still physiologically young, the graft of choice to consider is frequently hamstring autograft. Hamstring autograft has a lower failure and revision rate compared with allografts, and also avoids the donor site morbidity associated with BTB harvest. Although there may remain some residual laxity when compared with a BTB graft, it is unclear whether this difference is clinically relevant.

For older, less active patients, if nonoperative treatment fails, the graft of choice remains hamstring autograft; however, in patients willing to accept an increased risk of graft failure, allograft may be considered.

Copyright © 2020 Wolters Kluwer Health, Inc. All rights reserved.

CONCLUSIONS

Graft options for ACL reconstruction fall into 2 general categories, autograft and allograft. Frequently used autografts are BTB, quadriceps, and hamstring, whereas frequently used allografts include BTB, hamstring, tibialis anterior and posterior, peroneals, and Achilles. Biologically and biomechanically, the presence of a bone plug allows for bone-to-bone healing and retention of a normal native direct insertion site at the donor bone plug. In laboratory and clinical studies, autograft outperforms irradiated and processed allografts. Allograft may be considered for less active patients who are willing to accept an increased risk of graft failure. Within the autograft category, BTB has demonstrated the lowest failure rate and superior objective stability measurements; however, it is associated with increased anterior knee pain; overall clinical outcome scores are similar among the various autografts. The growing body of literature will continue to identify and provide further insight into the strengths and weaknesses of various graft types as we continue to refine our understanding of ACL healing and rehabilitation.

REFERENCES

1. Herzog MM, Marshall SW, Lund JL, et al. Trends in incidence of ACL reconstruction and concomitant procedures among commercially insured individuals in the United States, 2002-2014. *Sports Health*. 2018;10:523–531.
2. Beck NA, Lawrence JTR, Nordin JD, et al. ACL tears in school-aged children and adolescents over 20 years. *Pediatrics*. 2017;139:e20161877.
3. Sanders TL, Pareek A, Kremers HM, et al. Long-term follow-up of isolated ACL tears treated without ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2017;25: 493–500.
4. Sanders TL, Kremers HM, Bryan AJ, et al. Is anterior cruciate ligament reconstruction effective in preventing secondary meniscal tears and osteoarthritis? *Am J Sports Med*. 2016;44:1699–1707.
5. Galatz LM, Gerstenfeld L, Heber-Katz E, et al. Tendon regeneration and scar formation: the concept of scarless healing. *J Orthop Res*. 2015;33:823–831.
6. Mehran N, Moutzouros VB, Bedi A. A review of current graft options for anterior cruciate ligament reconstruction. *JBJS Rev*. 2015;3:11.
7. Reinhardt KR, Hetsroni I, Marx RG. Graft selection for anterior cruciate ligament reconstruction: a level I systematic review comparing failure rates and functional outcomes. *Orthop Clin North Am*. 2010;41:249–262.
8. Samuelsen BT, Webster KE, Johnson NR, et al. Hamstring autograft versus patellar tendon autograft for ACL reconstruction: is there a difference in graft failure rate? A meta-analysis of 47,613 patients. *Clin Orthop Relat Res*. 2017;475:2459–2468.
9. Jones KG. Reconstruction of the anterior cruciate ligament. A technique using the central one-third of the patellar ligament. *J Bone Joint Surg Am*. 1963;45:925–932.
10. West RV, Harner CD. Graft selection in anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg*. 2005;13:197–207.
11. Park MJ, Lee MC, Seong SC. A comparative study of the healing of tendon autograft and tendon-bone autograft using patellar tendon in rabbits. *Int Orthop*. 2001;25:35–39.
12. Cooper DE, Deng XH, Burstein AL, et al. The strength of the central third patellar tendon graft: a biomechanical study. *Am J Sports Med*. 1993;21:818–824.
13. Noyes FR, Butler DL, Grood ES, et al. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am*. 1984;66:344–352.
14. Rodeo SA, Kawamura S, Kim HJ, et al. Tendon healing in a bone tunnel differs at the tunnel entrance versus the tunnel exit: an effect of graft-tunnel motion? *Am J Sports Med*. 2006;34: 1790–1800.
15. Mohtadi NG, Chan DS, Dainty KN, et al. Patellar tendon versus hamstring tendon autograft for anterior cruciate ligament rupture in adults. *Cochrane Database Syst Rev*. 2011; 7:CD005960.
16. Persson A, Fjeldsgaard K, Gjertsen JE, et al. Increased risk of revision with hamstring tendon grafts compared with patellar tendon grafts after anterior cruciate ligament reconstruction: a study of 12,643 patients from the Norwegian Cruciate Ligament Registry, 2004-2012. *Am J Sports Med*. 2014;42:285–291.
17. Leys T, Salmon L, Waller A, et al. Clinical results and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction: a prospective study of hamstring and patellar tendon grafts. *Am J Sports Med*. 2012;40:595–605.
18. Gabler CM, Jacobs CA, Howard JS, et al. Comparison of graft failure rate between autografts placed via an anatomic anterior cruciate ligament reconstruction technique: a systematic review, meta-analysis, and meta-regression. *Am J Sports Med*. 2016;44: 1069–1079.
19. Benner RW, Shelbourne KD, Freeman H. Infections and patellar tendon ruptures after anterior cruciate ligament reconstruction: a comparison of ipsilateral and contralateral patellar tendon autografts. *Am J Sports Med*. 2011;39:519–525.
20. Papageorgiou CD, Kostopoulos VK, Moebius UG, et al. Patellar fractures associated with medial-third bone-patellar tendon-bone autograft ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2001;9:151–154.
21. Piva SR, Childs JD, Klucinec BM, et al. Patella fracture during rehabilitation after bone-patellar tendon-bone anterior cruciate ligament reconstruction: 2 case reports. *J Orthop Sports Phys Ther*. 2009;39:278–286.
22. Stein DA, Hunt SA, Rosen JE, et al. The incidence and outcome of patella fractures after anterior cruciate ligament reconstruction. *Arthroscopy*. 2002;18:578–583.
23. Lee GH, McCulloch P, Cole BJ, et al. The incidence of acute patellar tendon harvest complications for anterior cruciate ligament reconstruction. *Arthroscopy*. 2008;24:162–166.
24. Thompson SM, Salmon LJ, Waller A, et al. Twenty-year outcome of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon or hamstring autograft. *Am J Sports Med*. 2016;44: 3083–3094.
25. Tomita F, Yasuda K, Mikami S, et al. Comparisons of intraosseous graft healing between the doubled flexor tendon graft and the bone-patellar tendon-bone graft in anterior cruciate ligament reconstruction. *Arthroscopy*. 2001;17:461–476.
26. Maletis GB, Inacio MC, Desmond JL, et al. Reconstruction of the anterior cruciate ligament: association of graft choice with increased risk of early revision. *Bone Joint J*. 2013;95-b: 623–628.
27. Rahr-Wagner L, Thillemann TM, Pedersen AB, et al. Comparison of hamstring tendon and patellar tendon grafts in anterior cruciate ligament reconstruction in a nationwide population-based cohort study: results from the danish registry of knee ligament reconstruction. *Am J Sports Med*. 2014;42:278–284.
28. Conte EJ, Hyatt AE, Gatt CJ Jr, et al. Hamstring autograft size can be predicted and is a potential risk factor for anterior cruciate ligament reconstruction failure. *Arthroscopy*. 2014;30: 882–890.
29. Mariscalco MW, Flanigan DC, Mitchell J, et al. The influence of hamstring autograft size on patient-reported outcomes and risk of revision after anterior cruciate ligament reconstruction: a multicenter orthopaedic outcomes network (MOON) cohort study. *Arthroscopy*. 2013;29:1948–1953.
30. Snaebjornsson T, Hamrin Senorski E, Ayeni OR, et al. Graft diameter as a predictor for revision anterior cruciate ligament reconstruction and KOOS and EQ-5D values: a cohort study from the Swedish National Knee Ligament Register based on 2240 patients. *Am J Sports Med*. 2017;45:2092–2097.
31. Spragg L, Chen J, Mirzayan R, et al. The effect of autologous hamstring graft diameter on the likelihood for revision of anterior cruciate ligament reconstruction. *Am J Sports Med*. 2016;44:1475–1481.

32. Lautamies R, Harilainen A, Kettunen J, et al. Isokinetic quadriceps and hamstring muscle strength and knee function 5 years after anterior cruciate ligament reconstruction: comparison between bone-patellar tendon-bone and hamstring tendon autografts. *Knee Surg Sports Traumatol Arthrosc*. 2008;16: 1009–1016.
33. Adachi N, Ochi M, Uchio Y, et al. Harvesting hamstring tendons for ACL reconstruction influences postoperative hamstring muscle performance. *Arch Orthop Trauma Surg*. 2003;123: 460–465.
34. Mohammadi F, Salavati M, Akhbari B, et al. Comparison of functional outcome measures after ACL reconstruction in competitive soccer players: a randomized trial. *J Bone Joint Surg Am*. 2013;95:1271–1277.
35. Feller JA, Webster KE. A randomized comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction. *Am J Sports Med*. 2003;31:564–573.
36. Samuelsson K, Andersson D, Karlsson J. Treatment of anterior cruciate ligament injuries with special reference to graft type and surgical technique: an assessment of randomized controlled trials. *Arthroscopy*. 2009;25:1139–1174.
37. Anderson AF, Snyder RB, Lipscomb AB Jr. Anterior cruciate ligament reconstruction. A prospective randomized study of three surgical methods. *Am J Sports Med*. 2001;29:272–279.
38. Aglietti P, Giron F, Buzzi R, et al. Anterior cruciate ligament reconstruction: bone-patellar tendon-bone compared with double semitendinosus and gracilis tendon grafts. A prospective, randomized clinical trial. *J Bone Joint Surg Am*. 2004;86: 2143–2155.
39. Holm I, Oiestad BE, Risberg MA, et al. No differences in prevalence of osteoarthritis or function after open versus endoscopic technique for anterior cruciate ligament reconstruction: 12-year follow-up report of a randomized controlled trial. *Am J Sports Med*. 2012;40:2492–2498.
40. Magnussen RA, Carey JL, Spindler KP. Does autograft choice determine intermediate-term outcome of ACL reconstruction? *Knee Surg Sports Traumatol Arthrosc*. 2011;19:462–472.
41. Mohtadi N, Chan D, Barber R, et al. A randomized clinical trial comparing patellar tendon, hamstring tendon, and double-bundle ACL reconstructions: patient-reported and clinical outcomes at a minimal 2-year follow-up. *Clin J Sport Med*. 2015;25:321–331.
42. Mohtadi NGCDS. A randomized clinical trial comparing patellar tendon, hamstring tendon and double-bundle ACL reconstruction: patient-reported and clinical outcomes at five year follow-up. *J Bone Joint Surg*. 2019;101:949–960.
43. Brophy RH, Schmitz L, Wright RW, et al. Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the Multicenter Orthopaedic Outcomes Network (MOON) group. *Am J Sports Med*. 2012;40:2517–2522.
44. Shelton WR, Fagan BC. Autografts commonly used in anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg*. 2011;19: 259–264.
45. Slone HS, Romine SE, Premkumar A, et al. Quadriceps tendon autograft for anterior cruciate ligament reconstruction: a comprehensive review of current literature and systematic review of clinical results. *Arthroscopy*. 2015;31:541–554.
46. Lund B, Nielsen T, Faunø P, et al. Is quadriceps tendon a better graft choice than patellar tendon? A prospective randomized study. *Arthroscopy*. 2014;30:593–598.
47. Kim SJ, Kumar P, Oh KS. Anterior cruciate ligament reconstruction: autogenous quadriceps tendon-bone compared with bone-patellar tendon-bone grafts at 2-year follow-up. *Arthroscopy*. 2009;25:137–144.
48. Han HS, Seong SC, Lee S, et al. Anterior cruciate ligament reconstruction: quadriceps versus patellar autograft. *Clin Orthop Relat Res*. 2008;466:198–204.
49. Cavaignac E, Coulin B, Tscholl P, et al. Is quadriceps tendon autograft a better choice than hamstring autograft for anterior cruciate ligament reconstruction? A comparative study with a mean follow-up of 3.6 years. *Am J Sports Med*. 2017;45:1326–1332.
50. Runer A, Wierer G, Herbst E, et al. There is no difference between quadriceps- and hamstring tendon autografts in primary anterior cruciate ligament reconstruction: a 2-year patient-reported outcome study. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:605–614.
51. Budny J, Fox J, Rauh M, et al. Emerging trends in anterior cruciate ligament reconstruction. *J Knee Surg*. 2017;30:63–69.
52. Tibor L, Chan PH, Funahashi TT, et al. Surgical technique trends in primary ACL reconstruction from 2007 to 2014. *J Bone Joint Surg Am*. 2016;98:1079–1089.
53. Lansdown DA, Riff AJ, Meadows M, et al. What Factors influence the biomechanical properties of allograft tissue for acl reconstruction? A Systematic Review. *Clin Orthop Relat Res*. 2017;475:2412–2426.
54. Almqvist KF, Jan H, Vercruysse C, et al. The tibialis tendon as a valuable anterior cruciate ligament allograft substitute: biomechanical properties. *Knee Surg Sports Traumatol Arthrosc*. 2007;15: 1326–1330.
55. DiBartola AC, Everhart JS, Kaeding CC, et al. Maximum load to failure of high dose versus low dose gamma irradiation of anterior cruciate ligament allografts: a meta-analysis. *Knee*. 2016;23:755–762.
56. Fideler BM, Vangsness CT Jr, Lu B, et al. Gamma irradiation: effects on biomechanical properties of human bone-patellar tendon-bone allografts. *Am J Sports Med*. 1995;23:643–646.
57. Schwartz HE, Matava MJ, Proch FS, et al. The effect of gamma irradiation on anterior cruciate ligament allograft biomechanical and biochemical properties in the caprine model at time zero and at 6 months after surgery. *Am J Sports Med*. 2006;34:1747–1755.
58. Elenes EY, Hunter SA. Soft-tissue allografts terminally sterilized with an electron beam are biomechanically equivalent to aseptic, nonsterilized tendons. *J Bone Joint Surg Am*. 2014;96: 1321–1326.
59. Hoburg A, Keshlaf S, Schmidt T, et al. High-dose electron beam sterilization of soft-tissue grafts maintains significantly improved biomechanical properties compared to standard gamma treatment. *Cell Tissue Bank*. 2015;16:219–226.
60. Tejwani SG, Chen J, Funahashi TT, et al. Revision risk after allograft anterior cruciate ligament reconstruction: association with graft processing techniques, patient characteristics, and graft type. *Am J Sports Med*. 2015;43:2696–2705.
61. Swank KR, Behn AW, Dragoo JL. The effect of donor age on structural and mechanical properties of allograft tendons. *Am J Sports Med*. 2015;43:453–459.
62. Krych AJ, Jackson JD, Hoskin TL, et al. A meta-analysis of patellar tendon autograft versus patellar tendon allograft in anterior cruciate ligament reconstruction. *Arthroscopy*. 2008;24: 292–298.
63. Kraeutler MJ, Bravman JT, McCarty EC. Bone-patellar tendon-bone autograft versus allograft in outcomes of anterior cruciate ligament reconstruction: a meta-analysis of 5182 patients. *Am J Sports Med*. 2013;41:2439–2448.
64. Park SS, Dwyer T, Congiusta F, et al. Analysis of irradiation on the clinical effectiveness of allogenic tissue when used for primary anterior cruciate ligament reconstruction. *Am J Sports Med*. 2015;43:226–235.
65. Tian S, Wang B, Liu L, et al. Irradiated hamstring tendon allograft versus autograft for anatomic double-bundle anterior cruciate ligament reconstruction: midterm clinical outcomes. *Am J Sports Med*. 2016;44:2579–2588.
66. Mariscalco MW, Magnussen RA, Mehta D, et al. Autograft versus nonirradiated allograft tissue for anterior cruciate ligament reconstruction: a systematic review. *Am J Sports Med*. 2014;42:492–499.
67. Maletis GB, Chen J, Inacio MCS, et al. Increased risk of revision after anterior cruciate ligament reconstruction with bone-patellar tendon-bone allografts compared with autografts. *Am J Sports Med*. 2017;45:1333–1340.
68. Kaeding CC, Aros B, Pedroza A, et al. Allograft versus autograft anterior cruciate ligament reconstruction: predictors

of failure from a MOON prospective longitudinal cohort. *Sports Health*. 2011;3:73–81.
69. Fabricant PD, Jones KJ, Delos D, et al. Reconstruction of the anterior cruciate ligament in the skeletally immature athlete: a review of current concepts: AAOS exhibit selection. *J Bone Joint Surg Am*. 2013;95:e28.
70. Ardern CL, Ekas G, Grindem H, et al. 2018 International Olympic Committee consensus statement on prevention, diagnosis and management of paediatric anterior cruciate ligament (ACL) injuries. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:989–1010.
71. Kocher MS, Garg S, Micheli LJ. Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. Surgical technique. *J Bone Joint Surg Am*. 2006;88(suppl 1Pt 2):283–293.
72. Moksnes H, Engebretsen L, Risberg MA. The current evidence for treatment of ACL injuries in children is low: a systematic review. *J Bone Joint Surg Am*. 2012;94:1112–1119.
73. Kocher MS, Heyworth BE, Fabricant PD, et al. Outcomes of physeal-sparing ACL reconstruction with iliotibial band autograft in skeletally immature prepubescent children. *J Bone Joint Surg Am*. 2018;100:1087–1094.

Copyright © 2020 Wolters Kluwer Health, Inc. All rights reserved.