Chapter

Graft Choice in Anterior Cruciate Ligament Reconstruction

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Abstract

Anterior cruciate ligament (ACL) reconstruction is one of the most frequent surgical procedures performed by the sports medicine orthopedic surgeon. Many factors can influence the final outcome of the procedure, and the graft used is one of them. Over the years, the surgical technique has evolved and has been refined, including tunnel placement, graft fixation, and graft choice. For the latter, the main options available to the surgeon are autografts, which include patellar tendon, hamstring tendons, and quadriceps tendon autografts, allografts, and synthetic grafts. The ideal option for graft material, if there is one, is still to be determined. All graft options have advantages and disadvantages. Usually, the operating surgeon's preference or recommendation will determine the graft to be used, as such it is very important to have a complete knowledge of the advantages, disadvantages, and individual needs of each patient before making a decision. This chapter will focus on graft options for ACL reconstruction, evaluating the existing literature in order to provide an up-to-date review on the subject and, hopefully, contribute to an evidence-based decision for graft choice in ACL reconstruction.

Keywords: ACL reconstruction, graft options, autograft, allograft, hamstring graft, quadriceps graft, patellar tendon graft

1. Introduction

Rupture of the anterior cruciate ligament (ACL) is a very common injury, especially in sports-related activities, with an annual incidence of 68.6 per 100,000 person-years [1]. Also, the number of surgeries being performed annually for an ACL tear has increased over the years. In the United States alone, the rates of ACL reconstruction have increased significantly in a 12-year period from 10.36 to 18.06 and from 22.58 to 25.42 per 100,000 person-years for females and males, respectively [2–4].

The gold standard treatment for active patients with ACL rupture consists in surgically reconstructing this ligament. The principle of this surgical intervention is to re-establish stability and function in the knee, preventing further damage of the knee joint [5].

Given the rise in ACL injuries and ACL reconstruction revision rates, there has been an increased interest in research, goal being to improve outcomes, decrease morbidity, and lower revision rates [2]. Various grafts are available for ACL reconstruction, including autografts [bone-patellar tendon-bone (BTB), hamstring tendon (HT), quadriceps tendon (QT)], allografts and synthetic grafts.

The ideal graft for reconstruction of ACL is one which is biomechanically similar to the native ligament, can be easily harvested, has low harvest site morbidity, can be secured predictably, and gets well incorporated in the bone tunnels [3, 6]. When considering a graft source for the ACL reconstruction, the primary factor influencing a patient's decision is physician recommendation, hence the importance of a complete understanding of the graft options available [2, 7, 8].

2. Anatomy and function of the anterior cruciate ligament

The main function of the ACL is to provide anteroposterior and rotary stability to the knee. The ACL is the primary restraint to anterior translation of the tibia relative to the femur and is a major secondary restraint to internal rotation, particularly when the joint is near full extension [9].

It is composed of two functional bundles, based on their tibial insertion sites: the anteromedial (AM) and the posterolateral (PL) bundle [10]. These bundles function synergistically and have a distinct tensioning pattern throughout knee range of motion. When the knee is extended the PL bundle is tight, and the AM bundle is moderately lax. As the knee is flexed, the AM bundle tightens and the PL bundle loosens [11]. Also, biomechanical studies have shown that the PL bundle contributes the most to rotatory stability to the knee in lower degrees of flexion, and the anteromedial bundle provides more sagittal stability in higher degrees of flexion [2, 10]. In terms of dimensions, the ACL varies in length, ranging between 27 and 38 mm [12, 13]. There is also variability among individuals, in the femoral and tibial footprints of the ACL, with cross-sectional areas of 60–130 and 100–160 mm^2, respectively [12, 14, 15]. On average, the mid-substance of the ACL is 10 to 11 mm wide (range 7–17 mm) with an average thickness of 3.9 mm and a cross-sectional area of 40.9 ± 3 mm [2, 16].

Awareness of the overall dimensions of the native ACL, both the insertion sites and at its isthmus, is important when determining the size of the ACL graft and fixation angle during reconstruction [14].

With regard to structure, the ACL has a microstructure of collagen bundles of multiple types (mostly type I) and a matrix made of a network of proteins, glycoproteins, elastic systems, and glycosaminoglycans with multiple functional interactions [9]. Its sporadic fiber arrangement allows for a higher tensile strength than many other ligaments, with a maximum tensile strength reported as high as 2160 N (mean tensile strength approximately 1725 N), with a stiffness of 242 N/mm (mean stiffness 182 N/mm) and a strain rate of approximately 20% before failure [2, 17]. However, ultimate tensile load and linear stiffness decrease significantly with age: to 658 (129) N and 180 (25) N/mm, respectively, for older specimens (60–97 years) [9, 18].

3. Graft options

There are several options to consider when choosing a graft for ACL reconstruction. These options can be broken down to autografts, allografts, or synthetic grafts. The choice of graft should also be individualized to the patient's needs, anatomy, sport type, level of competition, and age. Another issue to consider is graft size, as it increases so does strength, but it also can lead to impingement with the notch and create arthrofibrosis [2, 19]. Recent studies have shown that graft size and tunnel positions should follow the patient's native anatomy in an attempt to reproduce and mimic the native ACL and improve long-term outcomes [20, 21]. It has been shown that anatomic ACL reconstructions reduce the risk of posttraumatic osteoarthritis (OA) at long-term follow-up [2, 22].

3.1 Autografts

Autografts are more commonly used than allografts and synthetic grafts [3]. In general, autografts are reported to have faster incorporation times, less failure rates overall, and no risk of disease transmission, but there is some morbidity with the graft harvest. Three main autografts are usually used: BTB, HT, and QT [2, 3, 23]. Furthermore, autografts are usually harvested from the ipsilateral extremity but can also be harvested from the uninjured knee. There are authors who advocate advantages of harvesting an autograft from the contralateral side [24].

3.1.1 Bone-patellar tendon-bone

BTB autograft (**Figure 1**) has historically served as the gold standard for ACL reconstruction mostly because of its long-standing track record and widespread use [2, 25]. The central third of the patellar tendon was also the first autograft option consistently used for ACL reconstruction [25]. One of the main advantages with this graft is that it allows fast bone to bone healing within the tibial and femoral tunnels [3]. Also, the clinical results reported are very good in terms of stability and return to play. The long-term results (17–20 years) have shown 83% of patients having stable, normal, or near-normal functions, and 1.6% of patients needed revision ACL reconstruction [3, 6]. More recent studies and meta-analyses have shown that BTB autografts have lower failure rates and higher return-to-sport rates compared with HT autografts, especially in the young athletic patient population [2, 26]. Some studies

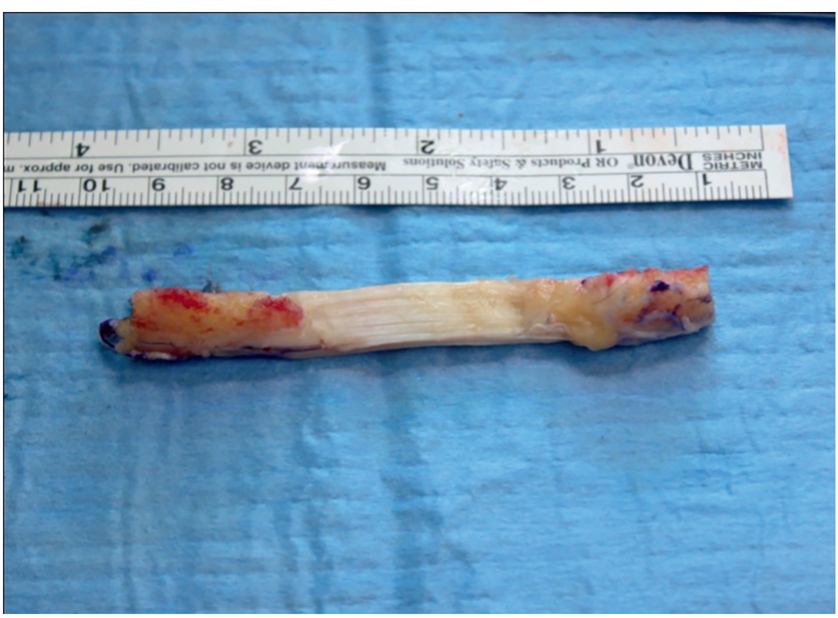

Figure 1.
BTB autograft.

have also found less residual anterior knee laxity and improved stability with the use of BTB autograft versus HT autograft at longer-term follow-up [26, 27].

Other long-term level I and II evidence studies comparing HT and BTB autografts have consistently shown no statistically significant difference in knee laxity [7, 28].

In terms of strength and stiffness, a 10-mm BTB graft has been found to resist to tensile loads of up to 2977 N with a stiffness of about 620 N/mm, numbers that exceed the strength and stiffness of the native ACL [29]. Donor site morbidity is another important aspect to consider when choosing a graft for ACL reconstruction.

In general, the patellar tendon graft is recognized as the graft with the highest harvest site morbidity, including anterior knee pain, kneeling pain, and patellar fracture [30]. If patellar fractures and patellar tendon ruptures are uncommon complications after BTB harvest, anterior knee pain has been frequently associated with BTB autograft use [2, 27, 30]. Some authors recommend that BTB graft for ACL reconstruction should be avoided in patients whose occupation or lifestyle requires frequent kneeling [3]. There is some evidence that anterior knee pain after ACL surgery may be more related to loss of motion and poor rehabilitation rather than graft choice, and studies have demonstrated a decrease in anterior knee symptoms after initiation of an accelerated rehabilitation program that emphasizes knee extension [2, 17]. Mismatch of BTB graft and tunnel length may also lead to a small tibial bone plug and compromise the strength of the fixation [31]. BTB autograft is also contraindicated in skeletally immature individuals as the graft harvest and fixation methods would violate the physes and increase the risk of growth arrest [2]. On the other hand, revision surgery, after a failed ACL reconstruction with BTB graft, may be easier as tunnel enlargement is not usually encountered as bone-to-bone healing prevents tunnel widening.

3.1.2 Hamstring tendons

HT autografts are currently the most popular graft choice for ACL reconstruction, having some key advantages. The semitendinosus tendon is the main graft that can be harvested with or without the gracilis tendon, usually from the ipsilateral leg. One attractive point is the minimally invasive nature of the harvest, thus minimizing donor site morbidity [3, 6]. Hamstring grafts are associated with lower risk of long-term anterior knee pain compared to BTB grafts [31]. Other advantages have been reported with the use of HT, including greater cross-sectional area, avoidance of the extensor mechanism in the graft harvesting process, and that it is an option for ACL reconstruction in the skeletally immature [2, 32].

With regard to strength and stiffness, a 4-strand HT graft has a tensile load of up to 4000 N with a stiffness of about 750 N/mm [33].

Clinical results are also good, but some studies are indicating more failures compared to BTB. In a meta-analysis in 2007, Poolman et al. showed reduced morbidity using HT autograft for ACL reconstruction. Authors stated that the modern endobutton hamstring graft fixation technique (two studies) yielded similar stability in the Lachman test as BTB grafts [34]. Another meta-analysis by Biau et al. from 6 published randomized clinical trials which included 423 patients with symptomatic unilateral ACL injury randomly assigned to reconstruction with patellar tendon or HT autograft showed postoperative knee instability was less common after ACL reconstruction with patellar tendon autograft than with HT autograft [35]. The difference was noted especially with the pivot-shift and for females and younger patients. Reinhardt et al. showed in systematic review, a graft failure rate lower for BTB than for HT (7.2 vs.

15.8%, respectively) (p = .02) [36]. Magnussen et al. showed, in a systematic review, graft failure lower for BTB compared to HT but without statistical significance [37]. There was no difference in patient-reported outcomes (IKDC). Anterior knee pain and kneeling pain were higher for BTB. More recently, in 2015, Xie et al. showed no difference in re-tear rate between patellar tendon and hamstrings and no difference for patient-reported outcome measures. However, reconstruction with patellar tendon graft resulted in better rotational stability and return to preinjury level of activity. Again, anterior knee pain and kneeling pain were greater for BTB [38].

Disadvantages associated with HT grafts include prolonged healing times, unpredictable graft size, higher failure rates in certain patient populations, and knee flexion weakness [2, 32]. The latter, risk of residual hamstring weakness, makes the graft a relative contraindication for athletes who need power in flexion for their athletic performance (i.e., sprinters, judo wrestlers) [2]. However, the main concern after HT autograft ACL reconstruction is graft failure. In particular, HT autograft seems to fail more among younger female patients, with graft rupture reported at 17.5% after HT autograft compared with 6.4% after BTB autograft in females aged 15 to 20 years [2, 39].

HT grafts less than 8 mm in diameter are a risk factor for poor patient outcomes, with an increase in failure rates, particularly in patients younger than 20 years [40]. This is of particular importance in hamstring autograft procedures because hamstring tendons, specifically in younger female population, tend to be insufficient and more prone to failure [41, 42]. Therefore, to address this issue, techniques that involve increasing hamstring graft thickness by folding the graft on top of itself have been developed [42]. The usual preparation technique for a HT graft is a doubled semitendinosus and gracilis resulting in a four-strand configuration as shown in **Figure 2** [43]. Another popular technique, in order to obtain a thicker graft, is a five-strand configuration, with a tripled semitendinosus and a doubled gracilis [42]. There is also the option of using a single tendon, usually the semitendinosus, in a 3- or 4-strand configuration. This technique can also be used with two suspensory devices for an all-inside ACL reconstruction [42, 44].

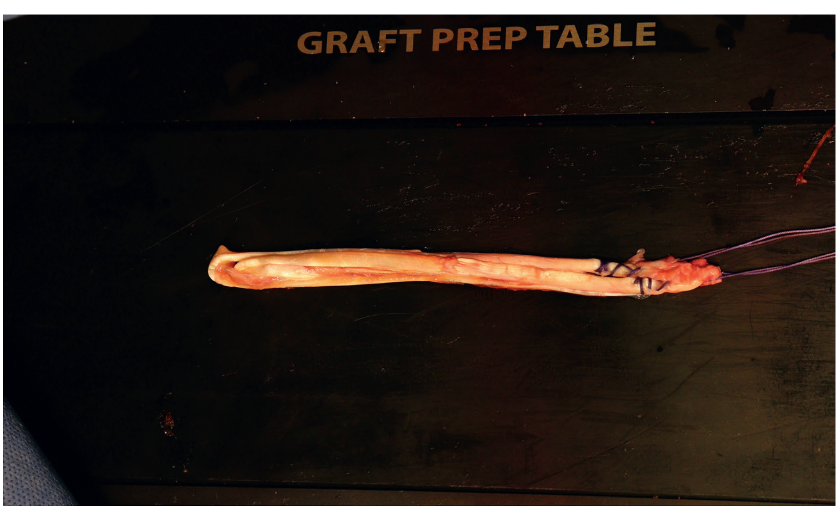

Figure 2.
Four-strand HT graft.

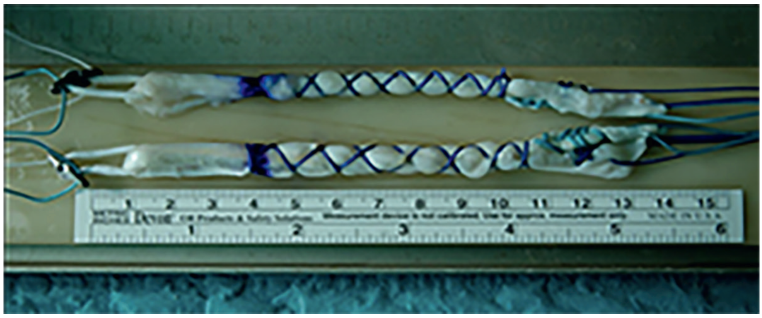

Figure 3.
HT graft prepared for a double-bundle ACL reconstruction.

HT grafts can be prepared as two individual grafts making the construct suitable for a double-bundle ACL reconstruction; the PL bundle is reconstructed using a double gracilis, and the AM bundle is reconstructed with a doubled semitendinosus (**Figure 3**).

3.1.3 Quadriceps tendon

The QT graft (**Figure 4**) is the least popular autograft source but has gained much attention in the last few years [45]. There are some important advantages reported with this graft, making it more and more appealing for ACL reconstruction. Among the proposed advantages are low morbidity at the harvest site [46, 47], predictable size and great versatility, the ability to harvest grafts in different widths, thicknesses, and lengths [23]. It can be harvested with or without a bone block as well as a full or partial thickness graft [48]. QT is a reliable and robust graft with a cross-sectional area up to twice that of a BTB autograft [2, 49]. The graft is longer and wider, has a higher tensile strength, about 50% more mass than a BTB autograft, and has been shown to be biomechanically similar to the six-strand HT autograft with regard to ultimate load to failure [2, 50]. It is also suitable for double-bundle ACL reconstruction [51]. The free quadriceps graft eliminates the risk of patella fracture and is also suitable for pediatric patients [52] (video link here).

Figure 4.
QT graft – Without a bone block.

The available data on QT for ACL reconstruction are limited, at least compared to HT and BTB grafts. Nonetheless, clinical results are promising. Lund et al. found no difference in anterior knee pain and functional outcomes in a prospective randomized trial comparing QT with patellar tendon. However, knee walking pain was significantly less for QT than with BTB [53]. A systematic review by Slone et al. in 2014 showed no difference for stability, range of motion, functional outcomes, and complications between quadriceps graft and BTB. Also, less donor site morbidity was found for QT [45]. A retrospective study by Geib et al. compared QT autografts with 30 BTB autograft reconstructions. The QT graft group was found to have a significantly lower percentage of knees with greater than 3 mm of side-to-side laxity on arthrometer testing when compared with the BTB group; however, no significant differences were found between the two groups on Lachman and pivot-shift testing [54]. A more recent meta-analysis evaluating 27 clinical studies with 2856 patients (Level of Evidence II) concluded that QT had similar graft survival rates and comparable functional and clinical outcomes when compared with BTB and HT autografts [2, 55]. QT also showed improved functional outcomes compared with HT autograft and significantly less harvest site pain compared with BTB autograft. A registry-based study did show a higher revision rate for QT (4.7%) versus HT and BTB (2.3% versus 1.5%, respectively), although QT patients in this study comprised only 3.2% of the patient sample and graft size, fixation technique, and bone block use were not available for analysis [2, 56].

3.2 Allograft

The main reason for allograft choice is the complete avoidance of graft harvest morbidity. Other advantages of allografts over autografts are shorter surgical times, predictable graft size, and easier recovery in the immediate postoperative period [2, 6]. Disadvantages include disease transmission, immunogenic response, weakening of graft tissues that occurs due to sterilization and processing techniques, and slower incorporation times [2, 3, 57, 58]. Also, the increased cost is another downside of using allografts, and they are not as widely available in other countries outside of the United States [2, 6].

The commonly used allografts for ACL reconstruction are BTB grafts, HT grafts, tibialis posterior/anterior, peroneal tendons, iliotibial band, and Achilles tendon [2, 6].

Allografts are prepared using deep freezing, radiation, chlorhexidine, or supercritical carbon dioxide, with these processing techniques affecting the overall structural and mechanical properties of allografts to varying extents, with inferior outcomes reported in irradiated and chemically processed allografts [31, 59]. Irradiated allografts are more likely to fail because of decreased mechanical properties due to sterilization and possibility of triggering an inflammatory response [3, 6]. The use of fresh frozen and non-irradiated allografts is reported to improve graft survival rates and could be a better option compared to irradiated allografts [31].

Regarding outcomes after ACL reconstruction with allograft, studies have consistently shown that allografts have a higher re-rupture rate than autografts in young, athletic individuals [2, 60]. Wasserstein et al. showed that in active patients aged <25 years, there was a 9.6% graft rupture rate with autograft versus 25.0% with allograft [61]. Another study found the use of allografts in primary ACL reconstruction to be associated with a 5.2 times greater risk of graft rupture compared to BTB autografts ($P < 0.01$), and patients under 30 years of age to be associated with increased risk of re-rupture [31, 60]. The study reported that by mid-30 years of age, there was no difference in graft rupture rate by graft choice. Even more studies have demonstrated that outcomes and revision rates after allograft use in patients who are aged >40 years are consistently similar to those after autograft ACL reconstructions [2, 62]. Recently, allograft use in young active patients is recognized as a risk factor for retear; graft choice by surgeons changed in the late period to use of allografts in older and less-active patients, which correlated with a significant decrease in retear risk [63]. Also, studies have shown slower incorporation times, revascularization, and "ligamentization" of allografts compared to autografts [64, 65]. However, this aspect alone does not explain the higher failure rates of allografts compared to autografts seen mainly in the young athletic population and not in the older, less demanding patients. Looking at the available data, the answer could be found in the sterilization process and the rehabilitation program. For example, in the study by Wasserstein et al. [61] who reported, on seven studies addressing patients aged less than 25 years, higher failure rates of allografts versus autografts, only two studies assessed autograft versus non-irradiated allograft, and in this analysis no statistically significant difference in graft failure was seen. Liu et al. [66] showed, in a recent systematic review, that non-irradiated allografts are superior to irradiated allografts based on improved knee joint functional scores and decreased failure rate. Also, Wang et al. [67] performed a meta-analysis looking at autograft versus non-irradiated and irradiated allografts. A total of 1172 patients were involved with mean patient age varying from 22 to 32.8 years. Although autograft offered greater advantages in functional outcomes and adverse events than irradiated allograft in ACL reconstruction, there were no significant differences between autograft and non-irradiated allograft in ACL reconstruction. On the other hand, other studies still show a higher failure rate in young patients treated with allograft tissue even with non-irradiated allografts [68]. Another theory that could explain higher rates of failure of allografts in younger patients is looking at rehabilitation. Mainly, donor site morbidity from graft harvest is eliminated when using allograft and patients are tempted to push the boundaries of their rehabilitation [69].

Another important role for allografts is revision ACL surgery. Large allografts, such as Achilles or QT, afford the additional advantage of a large cross-sectional area to fill large tunnels, have favorable time-zero biomechanical strength, and have a bone plug for bone-to-bone healing and fixation in at least a single tunnel. A study of the epidemiology of the Multicenter ACL Revision Study (MARS) cohort demonstrated that 54% of the surgeons used an allograft at the time of revision compared with 27% of the patients having had an allograft at the time of their primary reconstruction [70]. Also, multi-ligament knee surgery is another common scenario for the use of allograft tissue. Allograft use is appealing in multi-ligament knee injuries because of the need for multiple grafts to be available, the poor condition of the autograft tissues, and the attempt to limit further damage to the patient by harvesting autografts [71].

3.3 Synthetic grafts

Synthetic grafts have been developed in an attempt to overcome the concerns and disadvantages with auto- and allografts. They became popular in 1980 and early 1990, but the initial enthusiasm was soon discarded as early generations synthetic grafts failed.

The Ligament Augment Reconstruction System (LARS) (Surgical Implants and Devices, Arc-sur-Tille, France) is a synthetic ligament scaffold composed of polyethylene terephthalate fibers. Chen et al. conducted a prospective cohort study in patients undergoing ACL reconstruction with HT autografts (n = 73) versus LARS (n = 38) with 10 years follow-up [31, 72]. The study showed no significant difference in ACL reconstruction with HT autograft and LARS group with respect to the graft failure, mean SSD difference, and overall IKDC score. Early subjective evaluation at 6 months showed improved outcomes in the LARS group compared to the HT autograft group. The authors concluded that primary ACL reconstruction using either synthetics with remnant preservation or hamstring autografts showed satisfactory outcomes, especially the long-term cumulative failure rate, at 10 years postoperatively. Patient-reported outcomes suggested that symptom relief and restoration of function might occur earlier in those with synthetics [72].

Also, the systematic review by Batty et al. presented data on the functional outcomes, complications, and patient-reported outcomes of synthetic grafts in cruciate ligament reconstruction [73]. The results of this systematic review suggest that the current synthetic designs do achieve a number of their intended goals, allowing restoration of knee stability and potentially a faster progression through postoperative rehabilitation. In the LARS ACL group, return to unrestricted sports was allowed between 2 and 6 months postoperatively. The authors also concluded that objective knee instability occurs at a rate of between 6% and 12% for the LARS. Earlier synthetic ligament device designs have higher rates of failure and rates of synovitis/sterile effusion. Results for newer-generation devices, specifically the LARS, appear to show lower reported rates of failure, revision, and sterile effusion/synovitis when compared with older devices. A limitation of this review is the paucity of well-conducted clinical trials included. In relation to the LARS device, there was only one RCT, so the results should therefore be interpreted with caution.

Currently used synthetic grafts for ACL reconstruction are ligament augmentation system (LARS and Leeds-Keio), augmentation being the key word. However, their use remains controversial [31].

4. Conclusion

There are many choices when it comes to graft selection for ACL reconstruction, and numerous patients and surgical factors contribute to selection of an ideal graft. The decision should be individualized to best match the patient's anatomy, age, needs, and expectations. It is important for surgeons to understand the best available evidence on graft choice. Based on the current literature, autograft seems to be superior to allograft with respect to graft failure, patient-reported outcomes, and return to sport in young, active patients. The most commonly used autografts for ACL reconstruction provide similar functional outcomes. BTB grafts are associated with more anterior knee pain and kneeling pain but have faster incorporation times and are still being accepted as the "gold standard" by some authors.

HT offers certain theoretical advantages in the subgroup of patients that do a lot of kneeling, with preexisting patellofemoral pain, patella alta, or in those with open physes. On the other hand, HT grafts may have slightly higher failure rates, especially when less than 8 mm in diameter; however, this could theoretically be managed by technical aspects like the 5–6 strands grafts. Also, potential hamstring weakness might be a concern in athletes.

QT seems to be a very versatile graft. In general, the results are similar with BTB but with less donor site morbidity.

Allografts should be used with caution in young athletes as they are reported to be a risk factor for graft failure in this group of patients. However, this risk appears to be mitigated to some extent with the use of fresh frozen non-irradiated allografts, with frequent use in the United States. Also, allograft plays an important role in patients over 35–40 years, in revision ACL reconstruction, and in multi-ligament knee injuries.

Synthetic grafts are still under evolution, and no perfect synthetic graft is available till date. However, a clear indication for the use of synthetic graft is ligament augmentation or bracing.

The treating surgeon should thus be familiar with all the ACL reconstruction options available to individualize and optimize each patient's treatment and outcomes.

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References

[1] Sanders TL, Maradit Kremers H, Bryan AJ, Larson DR, Dahm DL, Levy BA, et al. Incidence of anterior cruciate ligament tears and reconstruction: A 21-year population-based study. The American Journal of Sports Medicine. 2016;**44**(6):1502-1507. DOI: 10.1177/0363546516629944

[2] Buerba RA, Boden SA, Lesniak B. Graft selection in contemporary anterior cruciate ligament reconstruction. JAAOS Global Research & Reviews. 2021;**5**(10):e21.00230. DOI: 10.5435/JAAOSGlobal-D-21-00230

[3] Dhammi IK, Rehan-Ul-Haq, Kumar S. Graft choices for anterior cruciate ligament reconstruction. Indian Journal of Orthopaedics. 2015;**49**(2):127-128. DOI: 10.4103/0019-5413.152393

[4] Mall NA, Chalmers PN, Moric M, Tanaka MJ, Cole BJ, Bach BR Jr, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. The American Journal of Sports Medicine. 2014;**42**(10):2363-2370. DOI: 10.1177/0363546514542796

[5] Fleaca R, Prejbeanu R, Feier AM, Russu O, Todor A, Predescu V, et al. Single- or double-bundle technique in the anterior cruciate ligament reconstruction – Current concepts and review of the literature. Journal of Interdisciplinary Medicine. 2016;**1**(S2):8-12. DOI: 10.1515/jim-2016-0047

[6] Chechik O, Amar E, Khashan M, Lador R, Eyal G, Gold A. An international survey on anterior cruciate ligament reconstruction practices. International Orthopaedics. 2013;**37**(2):201-206. DOI: 10.1007/s00264-012-1611-9

[7] Macaulay AA, Perfetti DC, Levine WN. Anterior cruciate ligament graft choices. Sports Health. 2012;**4**(1):63-68. DOI: 10.1177/1941738111409890

[8] Cohen SB, Yucha DT, Ciccotti MC, Goldstein DT, Ciccotti MA, Ciccotti MG. Factors affecting patient selection of graft type in anterior cruciate ligament reconstruction. Arthroscopy. 2009;**25**(9):1006-1010. DOI: 10.1016/j.arthro.2009.02.010

[9] Kraeutler MJ, Wolsky RM, Vidal AF, Bravman JT. Anatomy and biomechanics of the native and reconstructed anterior cruciate ligament: Surgical implications. The Journal of Bone and Joint Surgery. American Volume. 2017;**99**(5):438-445. DOI: 10.2106/JBJS.16.00754

[10] Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Ménétrey J. Anatomy of the anterior cruciate ligament. Knee Surgery, Sports Traumatology, Arthroscopy. 2006;**14**(3):204-213. DOI: 10.1007/s00167-005-0679-9

[11] Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W. The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. The American Journal of Sports Medicine. 2007;**35**(2):223-227. DOI: 10.1177/0363546506294571

[12] Fox MA, Engler ID, Zsidai BT, Hughes JD, Musahl V. Anatomic anterior cruciate ligament reconstruction: Freddie Fu's paradigm. Journal of ISAKOS. 2022;**S2059-7754**(22):00078-00075. DOI: 10.1016/j.jisako.2022.08.003

[13] Cone SG, Howe D, Fisher MB. Size and shape of the human anterior cruciate

ligament and the impact of sex and skeletal growth: A systematic review. JBJS Reviews. 2019;**7**(6):e8. DOI: 10.2106/JBJS.RVW.18.00145

[14] Iriuchishima T, Ryu K, Aizawa S, Fu FH. Size correlation between the tibial anterior cruciate ligament footprint and the tibia plateau. Knee Surgery, Sports Traumatology, Arthroscopy. 2015;**23**(4):1147-1152. DOI: 10.1007/s00167-014-2927-3

[15] Caterev S, Todor A, Khallouki Y, Bota NC, Zejly M, Nistor DV. Correlations between the anterior cruciate ligament insertion sites dimensions and patient's physical characteristics: An arthroscopic study. Chirurgia. 2018;**31**:5-9. DOI: 10.23736/S0394-9508.17.04739-8

[16] Cheung SC, Allen CR, Gallo RA, Ma CB, Feeley BT. Patients' attitudes and factors in their selection of grafts for anterior cruciate ligament reconstruction. The Knee. 2012;**19**(1):49-54. DOI: 10.1016/j.knee.2010.11.009

[17] West RV, Harner CD. Graft selection in anterior cruciate ligament reconstruction. The Journal of the American Academy of Orthopaedic Surgeons. 2005;**13**(3):197-207. DOI: 10.5435/00124635-200505000-00006

[18] Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. The American Journal of Sports Medicine. 1991;**19**(3):217-225. DOI: 10.1177/036354659101900303

[19] Su AW, Storey EP, Lin SC, Forst B, Lawrence JT, Ganley TJ, et al. Association of the graft size and arthrofibrosis in young patients after primary anterior cruciate ligament reconstruction. The Journal of the American Academy of Orthopaedic Surgeons. 2018;**26**(23):e483-e489. DOI: 10.5435/JAAOS-D-17-00177

[20] Fu FH, van Eck CF, Tashman S, Irrgang JJ, Moreland MS. Anatomic anterior cruciate ligament reconstruction: A changing paradigm. Knee Surgery, Sports Traumatology, Arthroscopy. 2015;**23**(3):640-648. DOI: 10.1007/s00167-014-3209-9

[21] van Eck CF, Lesniak BP, Schreiber VM, Fu FH. Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. Arthroscopy. 2010;**26**(2):258-268. DOI: 10.1016/j.arthro.2009.07.027

[22] Rothrauff BB, Jorge A, de Sa D, Kay J, Fu FH, Musahl V. Anatomic ACL reconstruction reduces risk of post-traumatic osteoarthritis: A systematic review with minimum 10-year follow-up. Knee Surgery, Sports Traumatology, Arthroscopy. 2020;**28**(4):1072-1084. DOI: 10.1007/s00167-019-05665-2

[23] Todor A, Caterev S, Nistor DV, Khallouki Y. Free bone plug quadriceps tendon harvest and suspensory button attachment for anterior cruciate ligament reconstruction. Arthroscopy Techniques. 2016;**5**(3):e541-e544. DOI: 10.1016/j.eats.2016.02.001

[24] Shelbourne KD, Beck MB, Gray T. Anterior cruciate ligament reconstruction with contralateral autogenous patellar tendon graft: Evaluation of donor site strength and subjective results. The American Journal of Sports Medicine. 2015;**43**(3):648-653. DOI: 10.1177/0363546514560877

[25] Duchman KR, Lynch TS, Spindler KP. Graft selection in anterior cruciate ligament surgery: Who gets what

and why? Clinics in Sports Medicine. 2017;**36**(1):25-33. DOI: 10.1016/j.csm.2016.08.013

[26] Samuelsen BT, Webster KE, Johnson NR, Hewett TE, Krych AJ. Hamstring autograft versus patellar tendon autograft for ACL reconstruction: Is there a difference in graft failure rate? A meta-analysis of 47,613 patients. Clinical Orthopaedics and Related Research. 2017;**475**(10):2459-2468. DOI: 10.1007/s11999-017-5278-9

[27] Freedman KB, D'Amato MJ, Nedeff DD, Kaz A, Bach BR Jr. Arthroscopic anterior cruciate ligament reconstruction: A metaanalysis comparing patellar tendon and hamstring tendon autografts. The American Journal of Sports Medicine. 2003;**31**(1):2-11. DOI: 10.1177/03635465030310011501

[28] Holm I, Oiestad BE, Risberg MA, Aune AK. No difference in knee function or prevalence of osteoarthritis after reconstruction of the anterior cruciate ligament with 4-strand hamstring autograft versus patellar tendon-bone autograft: A randomized study with 10-year follow-up. The American Journal of Sports Medicine. 2010;**38**(3):448-454. DOI: 10.1177/0363546509350301

[29] Cooper DE, Deng XH, Burstein AL, Warren RF. The strength of the central third patellar tendon graft. A biomechanical study. The American Journal of Sports Medicine. 1993;**21**(6):818-823; discussion 823-4. DOI: 10.1177/036354659302100610

[30] Milankov M, Kecojević V, Rasović P, Kovacević N, Gvozdenović N, Obradović M. Disruption of the knee extensor apparatus complicating anterior cruciate ligament reconstruction. Acta Chirurgica Iugoslavica. 2013;**60**(2):13-21. DOI: 10.2298/aci1302013m

[31] Baawa-Ameyaw J, Plastow R, Begum FA, Kayani B, Jeddy H, Haddad F. Current concepts in graft selection for anterior cruciate ligament reconstruction. EFORT Open Reviews. 2021;**6**(9):808-815. DOI: 10.1302/2058-5241.6.210023

[32] Cerulli G, Placella G, Sebastiani E, Tei MM, Speziali A, Manfreda F. ACL reconstruction: Choosing the graft. Joints. 2013;**1**(1):18-24

[33] Hamner DL, Brown CH Jr, Steiner ME, Hecker AT, Hayes WC. Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: Biomechanical evaluation of the use of multiple strands and tensioning techniques. The Journal of Bone and Joint Surgery. American Volume. 1999;**81**(4):549-557. DOI: 10.2106/00004623-199904000-00013

[34] Poolman RW, Farrokhyar F, Bhandari M. Hamstring tendon autograft better than bone patellar-tendon bone autograft in ACL reconstruction: A cumulative meta-analysis and clinically relevant sensitivity analysis applied to a previously published analysis. Acta Orthopaedica. 2007;**78**(3):350-354. DOI: 10.1080/17453670710013915

[35] Biau DJ, Katsahian S, Kartus J, Harilainen A, Feller JA, Sajovic M, et al. Patellar tendon versus hamstring tendon autografts for reconstructing the anterior cruciate ligament: A meta-analysis based on individual patient data. The American Journal of Sports Medicine. 2009;**37**(12):2470-2478. DOI: 10.1177/0363546509333006

[36] Reinhardt KR, Hetsroni I, Marx RG. Graft selection for anterior cruciate ligament reconstruction: A level I systematic review comparing failure rates and functional outcomes. The

Orthopedic Clinics of North America. 2010;**41**(2):249-262. DOI: 10.1016/j.ocl.2009.12.009

[37] Magnussen RA, Carey JL, Spindler KP. Does autograft choice determine intermediate-term outcome of ACL reconstruction? Knee Surgery, Sports Traumatology, Arthroscopy. 2011;**19**(3):462-472. DOI: 10.1007/s00167-010-1277-z

[38] Xie X, Liu X, Chen Z, Yu Y, Peng S, Li Q. A meta-analysis of bone-patellar tendon-bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. The Knee. 2015;**22**(2):100-110. DOI: 10.1016/j.knee.2014.11.014

[39] Salem HS, Varzhapetyan V, Patel N, Dodson CC, Tjoumakaris FP, Freedman KB. Anterior cruciate ligament reconstruction in young female athletes: Patellar versus hamstring tendon autografts. The American Journal of Sports Medicine. 2019;**47**(9):2086-2092. DOI: 10.1177/0363546519854762

[40] Iriuchishima T, Shirakura K, Yorifuji H, Aizawa S, Fu FH. Size comparison of ACL footprint and reconstructed auto graft. Knee Surgery, Sports Traumatology, Arthroscopy. 2013;**21**(4):797-803. DOI: 10.1007/s00167-012-1949-y

[41] Barrett GR, Noojin FK, Hartzog CW, Nash CR. Reconstruction of the anterior cruciate ligament in females: A comparison of hamstring versus patellar tendon autograft. Arthroscopy. 2002;**18**(1):46-54. DOI: 10.1053/jars.2002.25974

[42] Vinagre G, Kennedy NI, Chahla J, Cinque ME, Hussain ZB, Olesen ML, et al. Hamstring graft preparation techniques for anterior cruciate ligament reconstruction. Arthroscopy Techniques. 2017;**6**(6):e2079-e2084. DOI: 10.1016/j.eats.2017.08.031

[43] Brown CH Jr. Editorial commentary: How to increase hamstring tendon graft size for anterior cruciate ligament reconstruction. Arthroscopy. 2018;**34**(9):2641-2646. DOI: 10.1016/j.arthro.2018.06.014

[44] Lubowitz JH. All-inside anterior cruciate ligament graft link: Graft preparation technique. Arthroscopy Techniques. 2012;**1**(2):e165-e168. DOI: 10.1016/j.eats.2012.06.002

[45] Diermeier T, Tisherman R, Hughes J, Tulman M, Baum Coffey E, Fink C, et al. Quadriceps tendon anterior cruciate ligament reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2020;**28**(8):2644-2656. DOI: 10.1007/s00167-020-05902-z

[46] Slone HS, Romine SE, Premkumar A, Xerogeanes JW. Quadriceps tendon autograft for anterior cruciate ligament reconstruction: A comprehensive review of current literature and systematic review of clinical results. Arthroscopy. 2015;**31**(3):541-554. DOI: 10.1016/j.arthro.2014.11.010

[47] Buescu CT, Onutu AH, Lucaciu DO, Todor A. Pain level after ACL reconstruction: A comparative study between free quadriceps tendon and hamstring tendons autografts. Acta Orthopaedica et Traumatologica Turcica. 2017;**51**(2):100-103. DOI: 10.1016/j.aott.2017.02.011

[48] Rabuck SJ, Musahl V, Fu FH, West RV. Anatomic anterior cruciate ligament reconstruction with quadriceps tendon autograft. Clinics in Sports Medicine. 2013;**32**(1):155-164. DOI: 10.1016/j.csm.2012.08.014

[49] Shani RH, Umpierez E, Nasert M, Hiza EA, Xerogeanes J. Biomechanical

comparison of quadriceps and patellar tendon grafts in anterior cruciate ligament reconstruction. Arthroscopy. 2016;**32**(1):71-75. DOI: 10.1016/j.arthro.2015.06.051

[50] Musahl V, Karlsson J. Anterior cruciate ligament tear. The New England Journal of Medicine. 2019;**380**(24):2341-2348. DOI: 10.1056/NEJMcp1805931

[51] Caterev S, Nistor DV, Todor A. Anatomic double-bundle anterior cruciate ligament reconstruction with a free quadriceps tendon autograft. Arthroscopy Techniques. 2016;**5**(5):e1063-e1067. DOI: 10.1016/j.eats.2016.05.015

[52] Marx RG, Hsu J, Fink C, Eriksson K, Vincent A, van der Merwe WM. Graft choices for pediatric anterior cruciate ligament reconstruction: State of the art. Journal of ISAKOS. 2023;**S2059-7754**(23):00001-00009. DOI: 10.1016/j.jisako.2023.01.001

[53] Lund B, Nielsen T, Faunø P, Christiansen SE, Lind M. Is quadriceps tendon a better graft choice than patellar tendon? A prospective randomized study. Arthroscopy. 2014;**30**(5):593-598. DOI: 10.1016/j.arthro.2014.01.012

[54] Geib TM, Shelton WR, Phelps RA, Clark L. Anterior cruciate ligament reconstruction using quadriceps tendon autograft: Intermediate-term outcome. Arthroscopy. 2009;**25**(12):1408-1414. DOI: 10.1016/j.arthro.2009.06.004

[55] Mouarbes D, Menetrey J, Marot V, Courtot L, Berard E, Cavaignac E. Anterior cruciate ligament reconstruction: A systematic review and meta-analysis of outcomes for quadriceps tendon autograft versus bone-patellar tendon-bone and hamstring-tendon autografts. The American Journal of Sports Medicine. 2019;**47**(14):3531-3540. DOI: 10.1177/0363546518825340

[56] Lind M, Strauss MJ, Nielsen T, Engebretsen L. Quadriceps tendon autograft for anterior cruciate ligament reconstruction is associated with high revision rates: Results from the Danish knee ligament registry. Knee Surgery, Sports Traumatology, Arthroscopy. 2020;**28**(7):2163-2169. DOI: 10.1007/s00167-019-05751-5

[57] Hu J, Qu J, Xu D, Zhou J, Lu H. Allograft versus autograft for anterior cruciate ligament reconstruction: An up-to-date meta-analysis of prospective studies. International Orthopaedics. 2013;**37**(2):311-320. DOI: 10.1007/s00264-012-1720-5

[58] Vyas D, Rabuck SJ, Harner CD. Allograft anterior cruciate ligament reconstruction: Indications, techniques, and outcomes. The Journal of Orthopaedic and Sports Physical Therapy. 2012;**42**(3):196-207. DOI: 10.2519/jospt.2012.4083

[59] Sun K, Tian S, Zhang J, Xia C, Zhang C, Yu T. Anterior cruciate ligament reconstruction with BPTB autograft, irradiated versus non-irradiated allograft: A prospective randomized clinical study. Knee Surgery, Sports Traumatology, Arthroscopy. 2009;**17**(5):464-474. DOI: 10.1007/s00167-008-0714-8

[60] Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Hewett TE, Flanigan DC, et al. Change in anterior cruciate ligament graft choice and outcomes over time. Arthroscopy. 2017;**33**(11):2007-2014. DOI: 10.1016/j.arthro.2017.06.019

[61] Wasserstein D, Sheth U, Cabrera A, Spindler KP. A systematic review of failed anterior cruciate ligament reconstruction with autograft compared with allograft in young patients. Sports Health. 2015;**7**(3):207-216. DOI: 10.1177/1941738115579030

[62] Maletis GB, Chen J, Inacio MC, Funahashi TT. Age-related risk factors for revision anterior cruciate ligament reconstruction: A cohort study of 21,304 patients from the Kaiser Permanente anterior cruciate ligament registry. The American Journal of Sports Medicine. 2016;**44**(2):331-336. DOI: 10.1177/0363546515614813

[63] Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, MOON Consortium, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: Prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. The American Journal of Sports Medicine. 2015;**43**(7):1583-1590. DOI: 10.1177/0363546515578836

[64] Scheffler SU, Schmidt T, Gangéy I, Dustmann M, Unterhauser F, Weiler A. Fresh-frozen free-tendon allografts versus autografts in anterior cruciate ligament reconstruction: Delayed remodeling and inferior mechanical function during long-term healing in sheep. Arthroscopy. 2008;**24**(4):448-458. DOI: 10.1016/j.arthro.2007.10.011

[65] Muramatsu K, Hachiya Y, Izawa H. Serial evaluation of human anterior cruciate ligament grafts by contrast-enhanced magnetic resonance imaging: Comparison of allografts and autografts. Arthroscopy. 2008;**24**(9):1038-1044. DOI: 10.1016/j.arthro.2008.05.014

[66] Liu Y, Liu X, Liu Y, Yang S. Comparison of clinical outcomes of using the nonirradiated and irradiated allograft for anterior cruciate ligament (ACL) reconstruction: A systematic review update and meta-analysis. Medicine (Baltimore). 2022;**101**(32):e29990. DOI: 10.1097/MD.0000000000029990

[67] Wang S, Zhang C, Cai Y, Lin X. Autograft or allograft? Irradiated or not? A contrast between autograft and allograft in anterior cruciate ligament reconstruction: A meta-analysis. Arthroscopy. 2018;**34**(12):3258-3265. DOI: 10.1016/j.arthro.2018.06.053

[68] Kane PW, Wascher J, Dodson CC, Hammoud S, Cohen SB, Ciccotti MG. Anterior cruciate ligament reconstruction with bone-patellar tendon-bone autograft versus allograft in skeletally mature patients aged 25 years or younger. Knee Surgery, Sports Traumatology, Arthroscopy. 2016;**24**(11):3627-3633. DOI: 10.1007/s00167-016-4213-z

[69] Hulet C, Sonnery-Cottet B, Stevenson C, Samuelsson K, Laver L, Zdanowicz U, et al. The use of allograft tendons in primary ACL reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2019;**27**(6):1754-1770. DOI: 10.1007/s00167-019-05440-3

[70] MARS Group, Wright RW, Huston LJ, Spindler KP, Dunn WR, Haas AK, et al. Descriptive epidemiology of the Multicenter ACL revision study (MARS) cohort. The American Journal of Sports Medicine. 2010;**38**(10):1979-1986. DOI: 10.1177/0363546510378645

[71] Strauss MJ, Varatojo R, Boutefnouchet T, Condello V, Samuelsson K, Gelber PE, et al. The use of allograft tissue in posterior cruciate, collateral and multi-ligament knee reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2019;**27**(6):1791-1809. DOI: 10.1007/s00167-019-05426-1

[72] Chen T, Zhang P, Chen J, Hua Y, Chen S. Long-term outcomes of anterior cruciate ligament reconstruction using either synthetics with remnant preservation or hamstring autografts: A 10-year longitudinal study. The American Journal of Sports

Medicine. 2017;**45**(12):2739-2750. DOI: 10.1177/0363546517721692

[73] Batty LM, Norsworthy CJ, Lash NJ, Wasiak J, Richmond AK, Feller JA. Synthetic devices for reconstructive surgery of the cruciate ligaments: A systematic review. Arthroscopy. 2015;**31**(5):957-968. DOI: 10.1016/j.arthro.2014.11.032