Review Article

Evolution of anterior cruciate ligament reconstruction & graft choice: a review

Dane R. G. Lind, Rohan S. Patil, Matthew A. Amunategui, Nicholas N. DePhillipo^

Department of Orthopedic Surgery, University of Pennsylvania, Philadelphia, PA, USA

Contributions: (I) Conception and design: NN DePhillipo, DRG Lind; (II) Administrative support: NN DePhillipo; (III) Provision of study materials or patients: DRG Lind, RS Patil, MA Amunategui; (IV) Collection and assembly of data: DRG Lind, RS Patil, MA Amunategui; (V) Data analysis and interpretation: DRG Lind, RS Patil, MA Amunategui; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Nicholas N. DePhillipo, PhD, MBA, ATC. University of Pennsylvania, 3401 Grays Ferry Ave., Bldg., 450, Philadelphia, PA 19146, USA. Email: Nickd.atc@gmail.com.

Abstract: The surgical treatment of anterior cruciate ligament (ACL) injuries dates back over 100 years from the present day [2022]. While open repair of the torn ACL was popularized in the early 1900s, the first ACL reconstructions utilized the fascia lata as a graft and other extra-articular stabilizing techniques. The first free tendon graft reported for ACL reconstructions was the quadriceps tendon (QT) in the 1930s, followed by the hamstrings tendon (HT), and then the patellar tendon. With improved understanding of the ACL anatomy and biomechanics and the invention of the arthroscope, ACL reconstruction evolved from open procedures to arthroscopic. Similarly, with the help of many surgeon-scientists who reported patient outcomes following ACL reconstruction with various techniques, graft choice evolved with the hamstrings and patellar tendon grafts becoming the dominant and preferred choice of both surgeons and patients. In present day, we see a resurgence of one of the original grafts reported, the QT, as well as primary ACL repair. Future research will result in continued advancements of ACL surgical techniques and graft harvesting, which will allow the orthopedic community (including patients and surgeons) to benefit from such innovations and advanced technologies.

Keywords: Anterior cruciate ligament (ACL); quadriceps tendon (QT); patellar tendon; hamstrings; autograft

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History of anterior cruciate ligament (ACL) surgery

ACL surgery was documented as early as 1895, when Sir Arthur Mayo-Robson performed what is said to be the first open ACL repair (1). William Battle published the successful outcome of his ACL repair 5 years later (2). As ACL repair became increasingly popular, many surgeons spoke out against this procedure, as it often resulted in general instability of the joint and surgeons had difficulty maintaining connection between the ACL and femur, resulting in insufficient proximal ligament repair (3). In an attempt to remedy the repair procedure's shortcomings, Erwin Payr outlined a procedure in 1927 using transosseous fascia lata loosely defined by Schindler as a "partial ACL reconstruction" (4,5).

Before Payr, Paul Wagner recommended use of the fascia for reconstruction in patients with ligaments with severe damage in 1913 (6). One of the first published ACL reconstructions was performed by Ivan Grekov in 1914, who boasted successful results following a free fascia graft (7).

^ ORCID: 0000-0001-8946-4028.

Building off of the literature supporting the partial ACL reconstruction using the fascia, William Hey Groves evolved this procedure by using the entire fascia lata in 1917, marking the true beginning of ACL reconstruction (8). The original Groves method saw improvement by Alwyn Smith, who felt that this procedure failed to address the necessary strengthening of the joint by forcing too much strain on the relocated fascia (9,10), and Groves himself, who felt his original method prompted diminished lateral stability by removing the fascia from its original position (11).

Although the ACL reconstruction outlined in the early 1900's would be later revitalized, this procedure saw a lull in support until the second half of the century. From the 1920's to the 1950's, with the exception of a few explorative reconstruction techniques, conservative treatment of torn ACLs was preferred. That is, rather than continuing with the path forged by Groves and Smith, surgeons believed that these operations should be used as a last resort, prioritizing less invasive techniques like immobilization and strengthening (4). This impression was echoed by surgeons like Hughston (12) and Quigley (13), who, as McCulloch *et al.* stated, "failed to recognize the importance of the ACL as the primary restraint to anterior translation of the tibia and the prevalence of isolated ACL rupture" (14).

1920's–1950's

Before widespread publication of ACL reconstruction success and availability of ACL insufficiency testing like the pivot shift and the Lachman test, surgeons in the first half of the 20th century explored many new grafts and reconstruction procedures (15,16). Bennett believed a knee could remain stable without an ACL as long as other ligaments, specifically the medial collateral ligament (MCL), were intact (17). He claimed success in all 6 patients in his 1926 study, when he used a free strip of fascia woven longitudinally along the medial joint line, then reefing the medial extensor retinaculum. In 1932, Cubbins *et al.* sought to improve Smith's method by using the biceps aponeurosis distally along with the iliotibial (IT) band, boasting 90% improved results (18). Cotton and Morrison (19), Bosworth and Bosworth (20), and Mauck (21) argued that a medial extra-articular reconstruction alone was enough to provide necessary stability of the joint in an ACL deficient knee. Campbell introduced the quadriceps tendon (QT) graft in 1936 and 1939 (22,23). Macey (24), Helfet (25), and Augustine (26) described their own techniques using the semitendinosus tendon graft. O'Donoghue argued that the hamstrings muscles were not in constant contraction during ambulation, so dynamic hamstring reconstruction would not replace the function of the damaged ACL (27-29). He reported success in his modified Groves method that used a thick strip of IT band. Hauser believed that a distally based strip of patellar tendon could replace the function of the ACL and reinforce other medial structures of the joint (30). Lindstrom reported that, because the meniscus is avascular fibrocartilage nourished by the synovial fluid, it is the ideal replacement for the ACL. He reported that 27 of his 34 patients showed improved joint stability and reasoned that the 7 non-successful reports came from incorrect drill hole placement (31).

As argued by Burnett (32), by the end of the 1950's the use of many different grafts had been identified, but there was no consensus as to which type was most beneficial. Moving into the 1960's, surgeons had introduced reconstructions using free fascia, the QT, hamstrings tendons (HTs), bone-patellar tendon-bone (BTB), and meniscus. Although these discoveries lay the foundation for the following generation of ACL reconstruction innovation, this time period was handicapped by a general belief that this procedure was only necessary in extreme situations (12,13). For that reason, the first half of the 20th century lacked graft 'trends', and rather can be characterized as a time of sporadic invention. However, many surgeons in this era advocated for the importance of this procedure. Campbell (22) stressed that young, athletic patients with unstable knees seek ACL reconstruction. O'Donoghue (28) fought to improve the care of college athletes while improving the ACL reconstruction procedure. Although the ACL reconstruction, specifically the evolution of graft choice, is manifested mostly in the last third of the century, it is important to recognize that innovation of this procedure and advocacy for athletes took place in earlier years too.

1960's and 1970's

During this time, the sports medicine community experienced its largest shift regarding the evolution of graft choice for ACL reconstruction. Before the 1970's, surgeons believed that the ACL did not need to be repaired except in serious cases. Feagin, MacIntosh, and Marshall combatted this notion in the 1970's, but initially argued in favor of primary repair (33-36). After follow-up reports that these primary repairs were unsuccessful, and MacIntosh resorting to fascia lata reconstruction, surgeons understood that

repair would not suffice in recovering knee stability, and thus turned to extra-articular reconstruction (37). However, these peripheral reconstructions resulted in long term instability, so surgeons began to emphasize the role of intra-articular grafts (38).

Jones [1963] and Brückner [1966] expanded the patellar tendon graft for ACL reconstructions that was first described by Campbell in 1936 (39,40). This method saw improvement by Albert Trillat, who utilized the distal attachment of the patellar tendon, and later by Franke who was the first reported to use a free BTB (41). It was believed that this use of a free graft afforded perfect anatomical position, and this technique was coined as the "gold standard" in ACL reconstruction for years to come. Although the BTB dominated much of the late 20th century, the procedure had its downfalls. It was associated with risk of patellar fracture, patellar tendinitis, residual flexion contracture, and anterior knee pain.

Galeazzi [1934], Macey [1939], and Cho [1975] all believed that the hamstrings could remedy these complications, whether it be through the gracilis or semitendinosus tendon (24,42,43). Du Toit [1967] passed the gracilis tendon through the joint and fixed it to the tibia, deeming this technique the "Lindemann procedure" (44), and boasted positive results that were later echoed by Thompson and colleagues [1978] who saw 7 of 8 patients return to sport after this procedure (45). In 1979, Marshall and colleagues developed a procedure using the QT as a graft (35). Although Campbell introduced the use of this graft as early as 1936, it is not until recently (2010s) that this graft became more frequently used (46).

In 1962, Masaki Watanabe performed the first arthroscopic meniscectomy using the Watanabe No. 21, an arthroscopic instrument he developed (47). His arthroscopic procedures would soon be in practice at the Toronto General Hospital [1965], presented the Orthopaedic Research and Education Foundation in Atlanta [1967], and taught in Philadelphia [1972]. As the benefits of surgery with this device became more widely understood, the International Arthroscopy Association formed in 1974, and the use of the arthroscope in the decades following would revolutionize the ACL reconstruction (48).

This period saw the beginning of the widespread use of the BTB method for ACL reconstruction, with the HT graft lingering not far behind, and QT graft getting its first real recognition. These intra-articular techniques would quickly prove that the use of fascia lata or extensor mechanisms were unnecessary. Watanabe's invention of the arthroscope would revolutionize ACL reconstruction and greatly improve visualization and accessibility, thereby completely changing surgical techniques in the coming decades.

1980's and 1990's

In 1985, Burnett and Fowler claimed that more literature on the ACL "had appeared in the past 5 years than in the preceding 80 years" (32). Interestingly, many of the major medical device companies that support arthroscopic sports medicine procedures, such as ACLR, were founded during this time period (i.e., Arthrex Inc. founded in 1981, DePuy Mitek Inc. founded in 1991). The incorporation of these orthopedic sports medicine companies may perhaps be related to the influx in research and evidenced-based findings that indicated the need for improved technologies and devices for supporting surgeons treating ACL injuries as well as to improve patient outcomes. Burnett and Fowler attributed this influx to more thought given to placement and viability of tissue grafts (49,50), study of blood supply to the patellar tendon graft (50-52), and deeper understanding of the strength of different graft tissues (53,54). The techniques developed in the 20th century for BTB and HT grafts are still used today, with modifications mainly in fixation techniques for the HT (38).

While its original usage was reported for improving visualization of the menisci, the arthroscope became a useful tool for ACL reconstruction in the 1980's. In 1980, Dr. David Dandy performed the first arthroscopic assisted intra-articular ACLR, combining a carbon fiber graft with a Macintosh lateral extra-articular tenodesis. Though he reported positive results, the graft soon failed (55). As surgeons became more adept at using the arthroscope, this instrument enhanced their ability to perform isolated intra-articular reconstructions. With this development, BTB and HT ACL reconstructions became easier and more effective, and these procedures further increased in popularity (14). Specifically, the introduction of the arthroscope allowed for these reconstructions to only require a single incision rather than the traditional two incisions. The ACL reconstruction requiring only one incision, described in 1992 by Hardin *et al.*, became popular in the 1990's when surgeons began to use intra-articular drilling of the femoral tunnel (56). The use of the arthroscope helped surgeons confirm the notion that extra-articular procedures were only necessary when there was additional unwanted knee instability.

In 1982, Lipscomb published the first paper that used

both the semitendinosus and gracilis (57). Variations of his procedure were used frequently, utilizing the graft as two-stranded or four-stranded (quadruple). Support of the HT graft in ACL reconstruction grew vastly when Zarins and Rowe published their technique in 1986 (58). Their procedure, which became widely popular in the late 1980's, used the semitendinosus in conjunction with the IT band. Authors reported that this procedure provided excellent stability, but the substantial dissection it required often resulted in severe pain and loss of knee motion.

2000's and 2010's

Founded in 1980 by John Feagin, the ACL Study Group was created to improve the techniques of ACL repair, rehabilitation, and injury prevention. The group, now expanded to ~150 international ACL experts, meets biannually to discuss and exchange relevant information regarding ACLR and management, and reports from this group are an accurate representation of the global trends in ACLR. Beginning in 1992, the group has compiled results of the surveys from these biannual meetings that ask surgeons to report their preferred graft at the time. Surgeons choose between BTB, HT, QT, and soft-tissue allograft. After compiling the results of these surveys from 1992 to 2020, the group argues that trends in ACLR graft choice can be broken down into four phases: BTB autograft dominant, BTB autograft dominant with increasing HT autograft, HT autograft dominant with decreasing BTB plus the emergence of allograft, and finally HT autograft dominant with steady BTB autograft and the emergence of QT autograft (46).

The ACL Study Group reports that BTB was the preferred graft for ACLR amongst surgeons until 2008, when the HT took over BTB in popularity. Since then, the two have remained the most popular graft choices, with BTB seeming to be most popular graft in the United States especially amongst professional and high-level collegiate athletes (59,60), and HT being cited as more popular internationally (61,62). Finding significant differences in the clinical outcomes of BTB versus HT grafts is difficult (63-67). However, the HT graft has become more popular in recent years after many studies cite that patients with BTB autograft have more significant anterior knee pain, pain with kneeling, and other comorbidities as a result of the invasive graft harvest. Also, a few studies have reported increased prevalence of post-traumatic osteoarthritis at 7 years when compared to HT graft patients, but this phenomenon remains inconclusive (68,69).

Although the ACL Study Group reports that, at its peak in 2018, only 10% of their surgeons identified the QT as their graft of choice for ACLR, this graft has established more support in recent years. Studies indicate that QT ACLR has resulted in improved patient reported outcomes, improved knee stability, and lower ACLR graft re-tear rate when compared to HT (70-72). One meta-analysis compared QT to HT and BTB and found similar outcomes regarding knee stability, functional outcomes testing, and graft re-tear risk (73). This study also found that QT resulted in less donor site morbidity than BTB and better Lysholm scores than HT. Additionally, a recent study by Horteur *et al.* demonstrated the efficacy of QT autograft for improved functional outcomes with no significant differences in quadriceps muscle weakness compared to HT autograft harvest (74). Although QT graft was utilized before the 21st century, and reports suggest it has similar outcomes to HT and BTB, the efficacy of this graft choice needs to be explored further.

The ACL Study Group also reported a spike in allograft popularity from 2006 to 2012. In 2013, a study of more than 16,000 ACLRs from a community-based registry reported that 40% of primary and nearly 80% of revision ACLRs were allografts (75). Many studies, however, have found that allografts are associated with higher rates of ACLR graft rupture compared to autografts, particularly in younger, more active patients. Kane *et al.* compared the outcomes of patients 25 years or younger who had ACLR using allograft versus autograft and found similar patient-rated outcomes but a significantly higher ACLR graft re-tear rate requiring revision surgery in those who had an allograft (76). A study of outcomes following primary ACLR using BTB allograft and BTB autograft in skeletally mature patients 18 years old or younger reported that allograft patients had a 15 times higher re-tear risk in the allograft group versus the autograft group (77). The abundance of research demonstrating the risks of allograft in younger, more active patients in the late 2000s and early 2010s could be explained by allografts decreasing popularity as a primary graft choice in ACLR (*Figure 1*).

Future outlooks

Despite initial popularity in the 1980s and 1990s, the use of synthetic grafts in ACLR has lacked support until recent renewed interest. Synthetic grafts were introduced to remedy the donor site morbidity and long rehabilitation

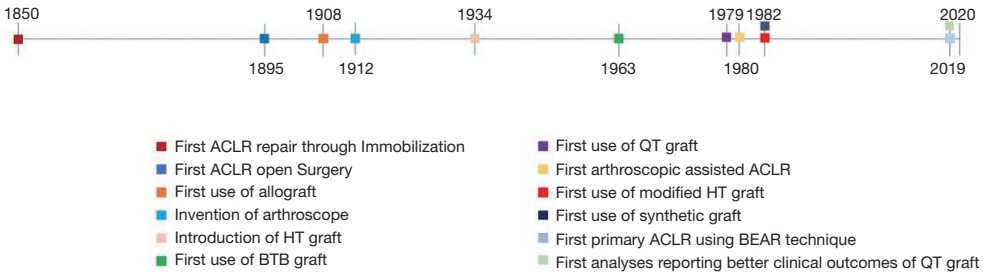

Figure 1 Evolution of ACL surgery and introduction of different autografts. ACLR, anterior cruciate ligament reconstruction; HT, hamstrings tendon; BTB, bone-patellar tendon-bone; QT, quadriceps tendon; BEAR, bridge-enhanced anterior cruciate ligament repair; ACL, anterior cruciate ligament.

period associated with ACLR autograft and have seen support due to their significant strength and the technically easier procedure (78). In the early 1900s and into the second half of the century, surgeons experimented with carbon fiber synthetic grafts in ACLR, resulting in poor resistance to torsion forces, carbon deposits in the liver, and surrounding tissue inflammation (79). In the coming years, surgeons would test the efficacy of Gore-Tex, Dacron, Kennedy LAD augmentation, and Polyester, none of which improved surgical outcomes, and many have been completely withdrawn from the market (78). However, synthetic grafts may have a future in ACLR, specifically the use of the Ligament Advanced Reinforcement System (LARS). Lavoie *et al.* reported high KOOS scores and Tegner activity level following ACLR with LARS (80). The same scientific group, in another study, found that LARS implantation in ACLR resulted in improved subjective and objective outcomes compared to BTB autograft in the year following surgery, although no differences were found 24 months postoperatively (81). In another study, LARS artificial ligaments resulted in excellent functional outcomes and showed higher knee stability than four-strand HT autografts at four years postoperatively (82). After years of failed synthetic graft exploration, these studies indicate that future expansion of the LARS artificial ligament reconstruction could pave the way for the future of synthetic ACLR.

Support for the bridge-enhanced anterior cruciate ligament repair (BEAR) procedure has led to a resurgence in ACL repair popularity in recent years. Founded in 2016 by Murray and colleagues, the BEAR procedure uses a specialized sponge made of organic material that is implanted at both ends of the torn ACL and is then injected with blood that promotes an enhanced healing process for both ends of the torn ACL (82). In 2019, Murray *et al.* compared the results of 9 BEAR patients to 7 patients receiving ACLR using HT autograft (83). They reported that 44% of the BEAR group had an IKDC grade A compared to only 29% in the ACLR group. Furthermore, the BEAR group had higher hamstring strength levels at 6, 12, and 24 months after surgery compared to the ACLR group. The same research group reestablished positive outcomes in a 2020 study comparing 65 BEAR patients to 35 autograft ACLR patients (33 HT and 2 BTB) (84). Two years postoperatively, the BEAR group had improved patient-reported outcomes, AP knee laxity, and hamstring muscle strength compared to the autograft ACLR group. Although further evidence is needed to support patient success, the BEAR procedure and primary ACL repair may be the next step in minimally invasive ACL surgery for the appropriate patient candidates.

Due to the magnitude of peer-reviewed research published on ACLR spanning over a century, this review has limitations. Most importantly, we acknowledge that this review of ACLR history is inadequate to represent the entire landscape of ACL reconstruction and graft choices. Rather, the purpose was to report the overall evolutionary changes since ACLR inception with focus on the traditional autograft choices (hamstring, patellar tendon, QT) and allografts. Additionally, there are many factors that may influence surgeon selection of ACLR grafts. These factors are both patient-related (i.e., age, sport, demographics) and surgeon-related (i.e., level of training, sports medicine fellowship, geography of practice/training, skill with harvesting various autografts).

Conclusions

Despite support in the early 1900s, and the pioneering of surgeons like Hey Groves, Smith, and Jones, ACL

reconstruction saw minimal support, growth, and improvement until the second half of the century. Feagin's creation of the ACL Study Group, Watanabe's arthroscope, and the improvement of procedures for ACLR using the patellar tendon, hamstrings, and QT allowed for ACL reconstruction to see its greatest advancements as the 20th century came to an end. With BTB autograft being the gold standard at the turn of the century, the next decade saw increased popularity of the HT graft and decreased popularity of BTB. In the 2010s, HT graft became most popular, with BTB close behind, QT growing in support, and a surge of allograft use. With these variations in graft choice, further research on patient-specific graft selection is needed to determine the optimal graft for patients undergoing ACLR.

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