Evolution of ACL Reconstruction

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Abstract

The tissue that would come to be known as the anterior cruciate ligament (ACL) was first described by the ancient Egyptians, but detailed examination of its structure and function did not began in earnest until the nineteenth century. Recognizing the important role of the ACL in stabilizing the knee, early attempts at suture repair through open surgical procedures were associated with high morbidity and poor outcomes. Open ACL reconstruction afforded more consistent stabilization, but it was the introduction of arthroscopy that allowed ACL reconstruction to become one of the most common orthopaedic surgical procedures. In seeking graft isometry, single-incision approaches with transtibial drilling of the femoral tunnel became standard of care, but subsequent biomechanical studies demonstrated that this technique failed to restore joint kinematics due to non-anatomic graft positioning. As a result, anatomic ACL reconstruction has rapidly grown in popularity, yet its ability to fully restore joint kinematics and prevent post-traumatic osteoarthritis (OA) requires further investigation. Elucidation of the multiple variables that contribute to knee stability will be necessary to further improve the treatment of ACL injury. Emerging surgical techniques, devices, and tissue-engineering strategies may also expand treatment strategies, including the possibility of augmented ACL repair for the appropriate indications.

Keywords

Anterior cruciate ligament · Reconstruction · Repair · Arthroscopy · Autograft · Allograft

First Description of ACL Structure and Function

The first description of the structure later known as the anterior cruciate ligament (ACL) dates back to ancient Egypt (3000 BC), with Hippocrates (460–370 BC) subsequently reporting a ligament pathology that produced anterior tibial subluxation [1, 2]. However, the Greek physician Claudius Galen (131–201 BC) gave the ACL its modern name, derived from the Greek "ligamenta genu cruciate." Despite its known existence for millennia, the function

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of the ACL was not formally investigated until more recent history. Brothers Wilhelm Weber (1804–1891) and Eduard Weber (1806–1871) demonstrated that transection of the ACL produced abnormal anterior–posterior movement of the tibia relative to the femur. They also reported that the ACL consisted of two bundles, which were tensioned at different degrees of knee flexion and differentially contributed to the roll and glide mechanism of knee.

Early Treatment of ACL Injury

The first case of ACL repair was performed in 1895 by Sir Arthur Mayo-Robson (1853–1933) and involved a 41-year-old miner [3]. Through an open procedure, the proximally torn ACL was sutured to the femoral insertion with catgut ligatures. At 6-year follow-up, the patient considered his leg "perfectly strong" but range of motion was objectively reduced. Following this first surgical report, suture repair grew to become the mainstay of the treatment for ACL tears until the early 1980s, a transition prompted by a seminal report in 1976 in which John Feagin and Walton Curl presented 5-year results of 32 Army cadets who had undergone direct ACL repair [4]. Almost all patients suffered some degree of instability, two-thirds experienced persistent pain, and 17 of 32 sustained a re-injury during the follow-up period. The authors concluded, "It was our hope that anatomic repositioning of the residual ligament would result in healing. Unfortunately, long-term follow-up evaluations do not justify this hope." Poor clinical outcomes with non-augmented ACL repair, coupled with improving techniques for ACL reconstruction (ACLR), hastened the move away from repair and toward reconstruction [5].

Emergence of ACL Reconstruction

Twenty-two years following the first report of ACL repair, Ernest William Hey Groves performed the first ACL reconstruction in 1917 [6]. He detached a strip of fascia lata from its tibial insertion and passed it from proximal to distal through femoral and tibial bone tunnels (Fig. 1). A year later (1918), Smith reported on nine cases he had treated with Hey Groves' technique. In 1919, Hey Groves presented an additional 14 cases in which he modified his method. Despite the promising results described by these early pioneers, debate in the following 50 years was less over primary ligament repair versus reconstruction, but whether any procedure should be performed at all. Nevertheless, novel (mostly open) reconstructive approaches were investigated in the ensuing half-century, including descriptions of various surgical techniques, graft sources, and fixation methods.

Graft Sources

Fascia lata. The fascia lata enjoyed early popularity as a graft for ACLR due to the seminal report by Hey Groves [6]. 100 years later (2017), the fascia lata still represents a viable autograft choice as its sizing is moderately

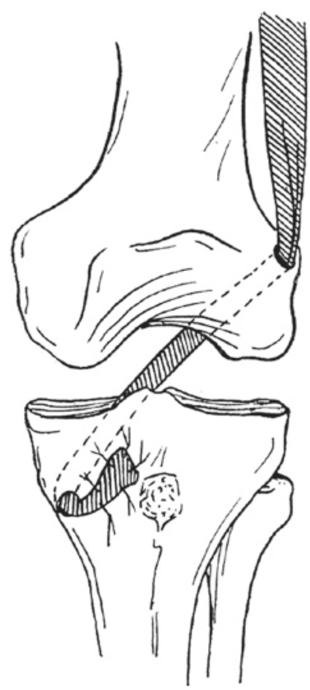

Fig. 1 Original Hey Groves ACL reconstruction technique in which a portion of the fascia lata was passed proximal to distal through bone tunnels. (Adapted with permission from *The Lancet*, Elsevier)(6)

tunable and its harvest has not been associated with the deficits in muscle strength induced by alternative grafts such as the hamstrings and quadriceps tendons [7].

Meniscus. Zur Verth replaced the ACL with the torn lateral meniscus, which he left attached distally and sutured against the ligament remnants proximally [1, 2]. The meniscus was seen as a suitable ACL replacement graft until the late 1970s when the contribution of the meniscus to knee stability and force transmission across the joint was increasingly appreciated. As a result, the meniscus was finally abandoned as a graft by the end of 1980s.

Bone–patellar tendon–bone (BPTB). The BPTB became one of the most common graft sources for ACLR, especially in patients seeking a fast return to sports. In 1976, Kurt Franke of Berlin reported good long-term functional outcomes following 130 ACL reconstructions using a free graft of the central third of the patellar tendon [8]. Given the promising long-term results, coupled with reliable and reproducible surgical technique, the BPTB became and remains one of the most popular graft sources [9, 10]. On the other hand, it became apparent that harvesting autogenous patellar tendon grafts could result in extension strength deficits and was more commonly associated with certain intraoperative and post-operative complications such as patellar fracture [11], patellar tendon rupture [12], flexion contracture, patellar tendonitis, and anterior knee pain [13–15]. In response, some surgeons started experimenting with using a central portion of the quadriceps tendon.

Quadriceps tendon. In 1984, Walter Blauth reported good results for 53 patients who underwent ACLR using quadriceps tendon [16]. The quadriceps tendon, however, never gained the same level of popularity as the BPTB or hamstring grafts despite experimental studies confirming its excellent mechanical properties [17]. Today, the quadriceps tendon is most commonly utilized as a secondary graft source in the revision setting or when other graft sources are compromised [18], but it is increasingly employed in primary ACLR.

Hamstrings tendons. The first use of hamstrings tendons as a graft was reported in 1934 by Italian orthopaedic surgeon Riccardo Galeazzi, who described a technique for ACL reconstruction using the semitendinosus tendon [1, 2, 19]. McMaster et al. in 1974 used the gracilis tendon alone [20]. In 1982, Brant Lipscomb started using both the semitendinosus and gracilis tendons as a double-strand graft left attached to the pes anserinus [21]. Six years later, following from Lipscomb's experience, Marc Friedman pioneered the use of an arthroscopically assisted four-strand hamstring autograft technique, which, despite several smaller modifications, set the standard for ACL reconstruction with hamstrings for the next 25 years [22]. Long-term follow-up studies have since confirmed almost equivalent results among graft choices regarding knee function and prevalence of osteoarthritis (OA) [23, 24].

Allograft. Allograft reconstruction of the ACL was an attractive proposition as it avoids the need for graft harvest and associated donor site morbidity and prevents weakening of external ligament and tendon structures which contribute to overall joint stability. In 1986, Konsei Shino and associates became one of the first groups to publish clinical results of 31 patients who had received allogenic reconstruction of the ACL utilizing mainly tibialis anterior and Achilles tendon allografts [25, 26]. After a minimum follow-up of 2 years, all but one patient had been able to return to full sporting activities. Subsequent publications by Richard Levitt and colleagues reported excellent results in 85% of cases at 4 years. These early reports of success paved the way for allografts to achieve relative popularity [27]. Unfortunately, the increased risk of viral disease transmission (e.g., HIV, Hepatitis C) associated with allografts in the 1990s created a significant setback for this technology. Allograft reconstruction has only recently regained some ground through the introduction of improved "graft-friendly" sterilization techniques [28]. Today, allograft tissue remains an attractive and reliable alternative to autograft in the primary and revision setting despite the rather considerable cost [29]. Furthermore, ACL reconstruction with allograft has an increased failure rate in young patients and should be avoided in this particular patient population if possible [30].

Synthetic. The use of synthetic materials has intrigued surgeons for over 100 years. It was hoped that use of synthetic grafts stronger than soft tissue equivalents could be developed, simplifying the operation by avoiding graft harvest and associated donor site morbidity. In terms of in vitro behavior, most synthetic grafts showed fatigue resistance on cyclic loading beyond the limit of human ligament endurance [31]. However, early biomechanical tests did not fully consider the biological environment in which the grafts would function. Stryker made a polyethylene terephthalate (i.e., Dacron) ligament replacement device commercially available in the 1980s. Poor outcomes were reported in 1997 by Wolfgang Maletius and Jan Gillquist at 9-year follow-up of 55 patients [32]. By that time, 44% of grafts had failed, 83% had developed radiographic signs of osteoarthritis, and only 14% presented with acceptable stability. The production of the Dacron ligament device was finally discontinued in 1994.

In the late 1970s, Jack Kennedy introduced a ligament augmentation device (LAD) made of polypropylene, which became known as the "Kennedy-LAD" [31]. Lars Engebretsen and associates commenced a randomized controlled study that enrolled 150 patients in 1990 to assess the merits of the LAD compared to acute repair and reconstruction with autologous BPTB [5]. Both acute repair and repair with the LAD failed in up to 30% of cases, and the authors hence discouraged any form of repair other than autograft reconstruction [33]. Various synthetic ACL grafts composed of other materials, including GoreTex, PDS, Eulit, and Polyflex, were introduced during the same period [34]. The hope of finding a reliable and durable off-the-shelf ACL replacement was soon dampened by a flood of reports on an increasing amount of fatigue failures, including graft re-rupture, chronic synovitis, tunnel widening through osteolysis, foreign body reaction, and poor incorporation of the synthetic grafts into the host bone [35, 36]. Nevertheless, the Kennedy-LAD, together with the Leeds-Keio and the LARS ligament, remain available as augmentation devices to this day.

Fixation Methods

For much of the twentieth century, fixation of the graft during ACL reconstruction entailed the simple suturing of the protruding parts of the graft to the periosteum at the tunnel exits. Kenneth Lambert was the first to describe the use of an interference screw. In 1983, Lambert used a standard 6.5 mm AO cancellous screws of 30 mm in length, which he passed from outside-in alongside the bone blocks of BPTB grafts [37]. Thereafter, interference screws gained wider attention due to Kurosaka's work examining the strength of various fixation methods, which he published in 1987 [38]. In this study, it was found that specially designed large diameter cancellous screws provided the strongest fixation. Within a few years, interference screws made of biodegradable materials such as PLA (polylactic acid), PGA (polyglycolic acid), and TCP (tri-calcium phosphate), or any combination thereof, also became available [39, 40] (Fig. 2). In 1994, Ben Graf, Joseph Sklar, Tom Rosenberg, and Michael Ferragamo introduced the Endobutton, a ligament suspensory device that works as a tissue anchor by locking itself against the cortex of the femoral condyle [41] (Fig. 3). Although critics have highlighted theoretical biomechanical disadvantages of suspensory fixation compared to aperture fixation, including the windshield wiper and bungee effects, clinical results between the various fixation methods have been relatively equivalent [42, 43].

Extra-Articular ACL Reconstruction

The complexities of intra-articular reconstructions were often fraught with peril and clinicians were eager to find ways to simplify stabilizing

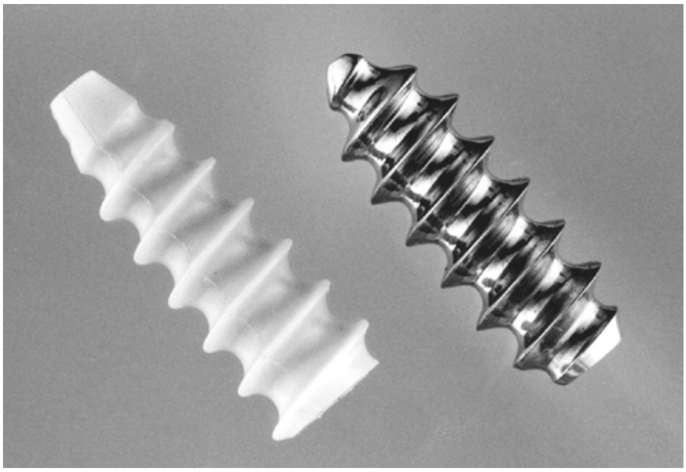

Fig. 2 Bioabsorbable and metal interference screws. (Adapted with permission from *Arthroscopy*, Elsevier) (40)

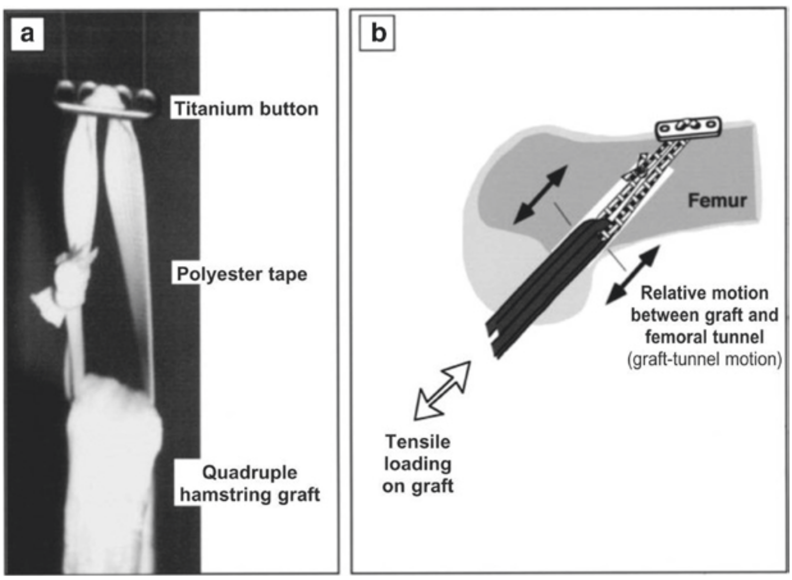

Fig. 3 **a** Femoral fixation construct for a quadruple-stranded hamstring graft with a polyester loop and Titanium Endobutton. **b** Schematic of graft-tunnel motion as it may occur when the graft is loaded either in cyclic tensile testing or in vivo during knee motion. (Adapted with permission from *KSSTA*, Springer Nature) (42)

procedures for ACL deficiencies without opening the joint. Various extra-articular substitution procedures with and without ACLR were developed and have since fallen out of practice. Most of those procedures addressed anterolateral instability, trying to control the pivot-shift phenomenon by using methods of capsular tightening, various tendon and fascial slings to re-route the iliotibial tract, and repositioning of ligament attachments [44]. Extra-articular reconstructions gradually fell out of favor when reports emerged about their unpredictability in satisfactorily decreasing tibial subluxation [45–47]. Most additional extra-articular procedures had vanished by the end of 1990s.

Emergence of Arthroscopy

Among various developments to improve the success of ACL reconstruction, one of the most profound advancements occurred in the 1970s, led by Robert Jackson and David Dandy, who improved arthroscopic instruments. The first arthroscopically assisted ACL reconstruction was performed by David Dandy in 1980 [48]. After several years of debate over the relative superiority of open versus arthroscopic surgery, Bray et al. reported in 1987 that arthroscopic ACL reconstruction was associated with less post-operative morbidity, improved cosmesis, increased speed of recovery, and greater range of motion [49]. It was during this time that the modern techniques of ACL reconstruction most firmly solidified, including the widespread use of arthroscopy fiber optic and television technology, a narrowing of the common graft source to BPTB and hamstrings, and confirmation of graft fixation methods.

Changing Paradigms—From Isometric to Anatomic Reconstruction

With a growing frequency of ACL reconstruction, there was a commensurate interest in understanding how to best perform the procedure. In the 1960s, based on the notion that the ideal anterior cruciate ligament graft should be isometric either in part or in the mechanical summation of its parts, the biomechanical concept of graft isometry arose [50]. The isometric point was defined by Artmann and Wirth in 1974 [2, 51]. In particular, the femoral tunnel was to be placed within the posterosuperior portion of the anatomic footprint, close to the "over-the-top" position. While the intention for isometric position was considered feasible through a single-incision approach with transtibial drilling, it became apparent that any non-anatomical single-bundle technique was unable to fully restore normal knee kinematics or reproduce normal ligament function. By extension, it was hypothesized that the relatively disappointing clinical results and high prevalence of osteoarthritis following ACL reconstruction were due to the inability to restore normal knee kinematics [52, 53].

As a result, the beginning of the twenty-first century saw a movement away from the concept of isometry and toward increased understanding of physiological and anatomical principles, led most prominently by Kazunori Yasuda and Freddie Fu [54]. In 1997, Sakane et al. examined the in situ force distribution between the anteromedial (AM) and posterolateral (PL) bundles, finding that the magnitude of forces in the PL bundle was significantly affected by the flexion angle while forces in the AM bundle remained relatively constant [55]. This study was the first to suggest that reconstruction techniques should focus on the role of both bundles. This prompted Fu to explore possible merits of anatomic ACL reconstruction [56–58] (Fig. 4).

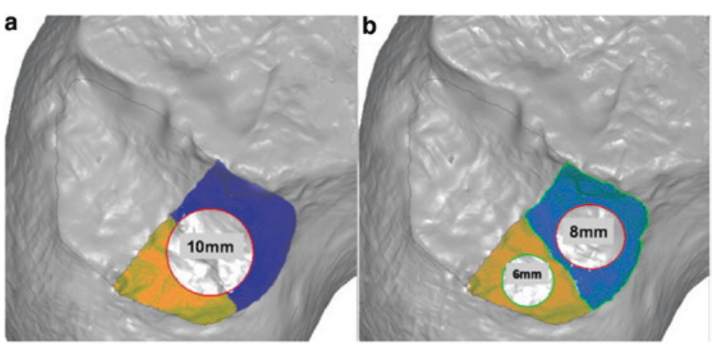

Fig. 4 Schematic of native femoral footprint on CT 3D reconstructed model showing potential position of one or two tunnels coinciding with single-bundle or double-bundle ACLR. (Adapted with permission from *Arthroscopy*, Elsevier) (57)

Contemporary ACL Reconstruction—From Anatomic ACLR to Individualized, Anatomic ACLR

As it became increasingly evident that reconstruction techniques were unable to restore normal knee kinematics and clinical results were still lacking, there was a shift in focus to the anatomy and physiology of ACLR [2]. In 1997, the importance of the two ACL bundles in providing stability to anterior tibial loads was shown in a biomechanical analysis [55]. This was the first study to suggest that taking both bundles into account during reconstruction may be necessary to reproduce the in situ forces of the native ACL. Traditional non-anatomic reconstructions were shown biomechanically to fail to limit anterior tibial translation in response to a combined valgus and internal tibial torsional force [59]. Anatomic double-bundle reconstruction most closely restored the knee kinematics and in situ ACL forces in response to both an anterior tibial load and combined rotatory load [52]. The biomechanical successes led to the interest in anatomic double-bundle ACLR for improving clinical outcomes [56]. Although the clinical outcomes of anatomic single-bundle versus anatomic double-bundle are not conclusive, the literature supports the focus remaining on the *anatomic* reconstruction [54, 57].

Non-anatomic femoral tunnel location has been identified as the most common reason for ACL graft failure in the Multicenter Anterior Cruciate Ligament Revision Study (MARS) database [60]. Additionally, worse clinical outcome measures have been correlated with femoral tunnels farther from the anatomic insertion site [9]. Given the focus on anatomic femoral tunnels, the transtibial ACLR technique has been questioned, and found that it does not consistently position the femoral tunnel in the anatomic ACL insertion site [61]. Thus, independent femoral tunnel reaming through an anteromedial portal has subsequently gained popularity. Anteromedial portal reaming has been shown to more accurately position the femoral tunnel in the center of the ACL footprint, as compared to transtibial drilling where the tunnel is consistently superior and anterior to the center of the footprint [62]. This has been reported in multiple studies and confirmed with a meta-analysis [63].

More recently, the anatomic approach has been refined to the "*individualized, anatomic ACLR concept*" [57, 64]. The primary objective is the functional restoration of the ACL to its native dimension, fiber orientation, and insertion sites. The literature has shown that excellent outcomes can be expected when either a single-bundle or double-bundle technique is individualized to the patient and tunnel placement is anatomic [65]. A crucial aspect is recreating the anatomy in an individualized manner based on the size of the native ACL and the bony morphology of the knee, and in this light, individualized graft sizing has become a more recent focus. The Multicenter Orthopaedic Outcomes Network (MOON) Cohort Study showed that ACL graft sizes 8 mm or less were associated with increased risk for revision surgery [66]. However, the size of the graft must be considered in relation to the individual patient's native anatomy (Fig. 5). Autograft reconstruction options, including quadriceps tendon, bone–patellar tendon–bone, and hamstrings tendon, vary in size for each patient and do not necessarily reliably recreate the native ACL size [67]. Additionally, these autograft options do not correlate well with patient characteristics, such as height and weight. Restoring the native ACL femoral and tibial insertion site size is recommended, but with the knowledge that the ACL midsubstance is about 50% of the cross-sectional area of the tibial insertion [68]. In the senior author's practice, a successful anatomic reconstruction aims to use a graft with an area between 50 and 80% of the native tibial insertion (Fig. 6).

As the individualized, anatomic ACLR concept has evolved so too has the surgical technique. The arthroscopic technique is optimized with a three-portal approach. A standard high anterolateral portal is initially used for access and diagnostic arthroscopy, followed by a transtendinous anteromedial portal for improved

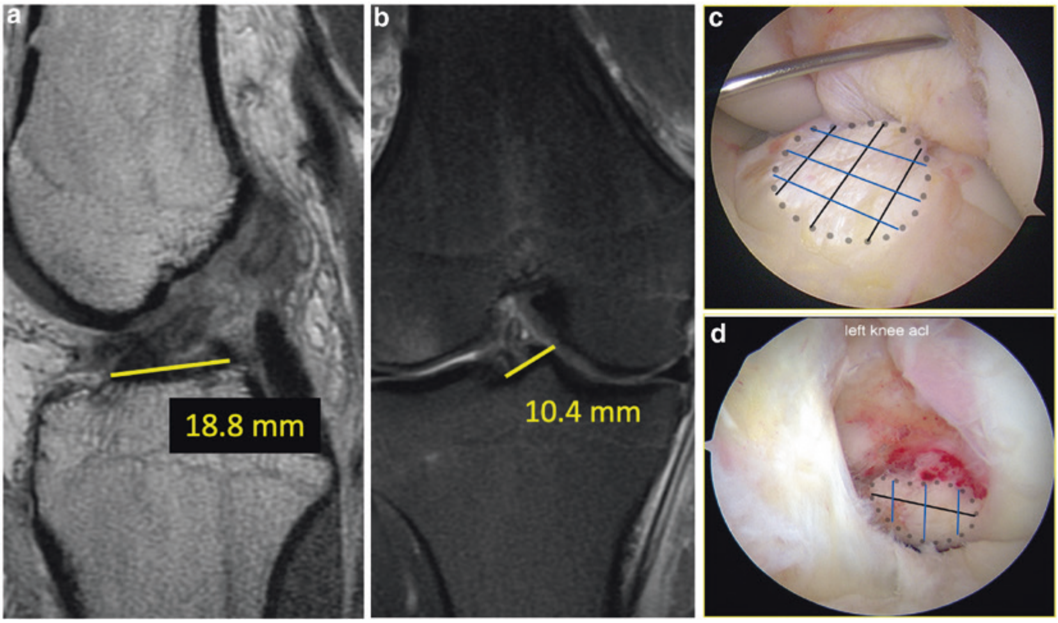

Fig. 5 Determination of native tibial insertion site dimensions of ACL, as performed for individualized anatomic ACLR. Measurement of **a** sagittal and **b** coronal ACL length at tibial insertion site on MRI. Intraoperative measurement of **c** tibial and **d** femoral insertion sites

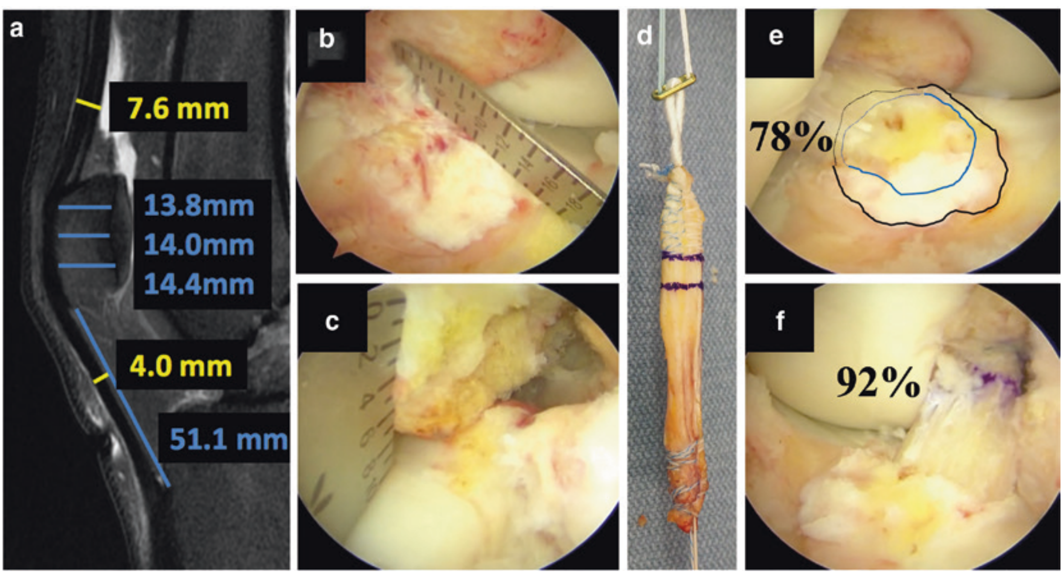

Fig. 6 Example of individualized anatomic ACLR case. **a** Preoperative measurement of potential autograft dimensions on MRI and ultrasound (not shown). Confirmation of **b** tibial and **c** femoral insertion sites with arthroscopic ruler. **d** Given this patient's sizing of possible grafts, native ACL dimensions, and sporting activity, a soft-tissue quadriceps tendon autograft was most appropriate. The graft restored **e** 78% of the native tibial insertion site area and **f** 92% of the native femoral insertion site area. Black lines outline native tibial footprint; blue lines outline graft footprint within native footprint

visualization of the femoral footprint, and an accessory anteromedial medial portal for transportal femoral tunnel reaming. The primary current day graft options include autograft quadriceps tendon with or without bone plug, autograft BPTB, and autograft hamstring tendons. Allografts are avoided in young patients when possible given the high rates of failure in the young athletic population [69]. Quadriceps tendon and patellar tendon thicknesses are measured preoperatively on MRI, and hamstring tendons are measured on ultrasound [70, 71]. The graft choice is individualized for each patient based on many factors including the size matching, patient age, and patient activity level. Soft tissue graft fixation is usually performed with suspensory fixation on the femoral side, but interference screws are also an option. To date, no one fixation technique has been shown to be superior [72]. Grafts with bone blocks are commonly fixed with interference screws, but again suspensory fixation is an option. Tibial sided fixation for all grafts most commonly performed with interference screws gives the ease of insertion.

Future of ACL Repair and Reconstruction

Anatomic ACLR and Post-Traumatic OA. The recent transition from transtibial to transportal drilling due to an intended transition from non-anatomic to anatomic ACL reconstruction has yet to permit long-term follow-up on the relative efficacy of anatomic ACLR. On the other hand, biomechanical and short-term clinical studies demonstrated superior objective stability following anatomic (versus non-anatomic) ACLR, while patient-reported outcomes were largely equivalent [73, 74]. Conversely, registry studies found that transportal drilling was associated with higher re-tear rates than transtibial drilling [75], while subsequent studies found no differences in failures rates between drilling techniques [76], suggesting a learning curve with transportal (i.e., anatomic) drilling. The abrupt transition from transtibial to transportal drilling also precludes randomized controlled trials comparing the two techniques.

In cohort studies employing quantitative MRI mapping of cartilage thickness, DeFrate and colleagues found increased cartilage thinning 2 years following non-anatomic ACLR, a phenomenon not seen in anatomically reconstructed knees [77, 78]. In one of the few long-term studies on outcomes following anatomic ACLR, Järvela et al. [79] found increased rates of OA in anatomically reconstructed knees, as compared to contralateral healthy knees, but an-anatomic ACLR group was not included. Consequently, while it appears that anatomic ACLR does not completely obviate the long-term incidence of post-traumatic OA, whether it mitigates the risk as compared to non-anatomic ACLR remains unclear. It is noteworthy that transportal drilling may be considered a prerequisite for anatomic tunnel positioning, yet does not guarantee successful placement. To that end, a recent systematic review evaluating purported "anatomic" ACLR studies found substantial underreporting of surgical details to adequately conclude that anatomic tunnel placement was likely achieved [80]. In light of these findings, the authors reaffirmed the need for improved surgical description in line with the previously validated anatomic ACL reconstruction scoring checklist (AARSC) [30].

Novel Imaging Modalities. Radiographic scales remain the gold standard for the diagnosis of OA, but the slow progression of arthritic changes following ACLR necessitates improved methodology for earlier diagnosis, which would then provide the theoretical prospect of preventative intervention. Novel sequences of MRI have shown promise in detecting early compositional and structural changes in the articular cartilage following trauma and surgery [81, 82]. In fact, a recent study by Chu et al. [83] utilizing ultrashort echo time (UTE)-T2* mapping suggested that perturbed cartilage could recover its native composition 2 years following anatomic ACLR. However, such findings are preliminary and require confirmation and further exploration. Given the post-traumatic upregulation in inflammatory mediators following ACL injury, it may also be possible (and necessary) to supplement ACLR with biological mediators to further reduce the risk of post-traumatic OA. For instance, Lattermann et al. have commenced a multicenter clinical trial and investigated the effect of pre-operative, intra-articular corticosteroid injection on joint health following ACLR [84].

Role of Anterolateral Complex. As anatomic ACLR has progressively supplanted non-anatomic techniques, recent debate regarding the anterolateral structures of the knee and their contributions to stability has arisen following the assertion of a discreet ligament in the anterolateral capsule, the putative anterolateral ligament (ALL) [85]. While numerous biomechanical studies have affirmed that the ACL is the primary restraint to anterior tibial translation and internal rotation [86–89], the anterolateral capsule and the capsulo-osseous layer of the iliotibial band (i.e., ALL) are secondary constraints. At a recent meeting of the anterolateral complex (ALC) Consensus Group, it was concluded that there is presently insufficient clinical evidence to support clear indications for lateral extra-articular procedures as an augmentation to ACL reconstruction [90]. Resolution of the current uncertainty would be facilitated by further elucidation of the contributions of numerous variables to rotatory stability, including meniscal tears, posteromedial meniscocapsular injury (i.e., ramp lesions), bony morphology, general laxity, and gender, among others [91]. Objective, quantitative measures of knee instability are also needed to better map injury to particular knee structures with worsening instability, of which there are several emerging devices [92, 93].

Augmented ACL Repair. The pursuit of improved outcomes and preservation of joint health following ACL injury have also renewed interest in ACL repair. While past studies of non-augmented suture repair reported high failure rates and poor outcomes, emerging advances in surgical techniques and technology may ultimately support ACL repair as a viable treatment strategy, given the appropriate indications [94]. ACL repairs augmented with either static or dynamic mechanical support have yielded equivocal outcomes. For instance, Gagliardi et al. [95] recently reported a failure rate of 48.8% within 3 years of static suture augmentation of ACL repair in pediatric patients (age 7–18), as compared to 4.7% in the age-matched ACL reconstruction cohort. Conversely, Hoogeslag et al. [96] found dynamic augmented ACL suture repair to be non-inferior to ACL reconstruction at 2-year follow-up when performed in adults.

In addition to mechanical support, biological augmentation may also be useful and/or necessary to overcome the poor healing microenvironment of the joint. To that end, Murray et al. recently reported the 2-year outcomes following biological scaffold (i.e., Bridge-Enhanced) ACL repair (BEAR), finding equivalence with the matched ACLR cohort [97]. The authors noted that the results are promising but preliminary, with longer follow-up and increased sample sizes needed. It also remains to be seen if the BEAR procedure can mitigate post-operative arthritic changes, as previously reported at 1 year in a large animal study performed by this same group [98].

Tissue-Engineered ACL Grafts. Lastly, the emerging field of tissue-engineering promises engineered grafts that overcome the past limitations of synthetic grafts, essentially providing an engineered autograft for an individual patient. One approach is to decellularize a xenograft or allograft, in theory eliminating the immunogenicity of foreign cells. Repopulation of the graft with the patient's cells, either exogenously delivered or endogenously recruited, would in effect provide an autograft without donor site morbidity. The optimized decellularization protocol should preserve the structural and biochemical cues of the native tissue, largely preserving native mechanical properties and promoting tissue-specific differentiation in repopulating progenitor cells. This strategy has shown positive results in preclinical studies [99] but translation to human patients is still unproven. An alternative approach is to fabricate a biomimetic scaffold, with or without cells, by engineering technologies. Scaffolds composed of aligned nano- or microfibers mimicking the aligned collagen fibrils of native tendon or ligament can be fabricated by electrospinning [100, 101] or knitting/weaving devices adapted from textile technology [102].

Conclusion

While the ACL has long been recognized as an important structure for knee stability, rigorous investigation of its function and reliable techniques for its restoration are a recent development of the past half-century. The introduction of arthroscopy reduced the morbidity of ACLR but indirectly encouraged enhanced surgical efficiency, in turn leading to single-incision transtibial drilling with resulting non-anatomic graft positioning. The contemporary transition to anatomic ACLR is supported by biomechanical and early clinical studies, but the ability of anatomic ACLR to restore native joint kinematics and prevent long-term OA progression remains under investigation. Lastly, emerging technologies offer tremendous promise in better understanding of the multifactorial nature of knee stability. With such understanding, coupled with improved surgical techniques and tissue-engineering strategies, the orthopaedic surgeon will be better equipped to provide the right treatment for each individual patient.

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