Biomechanical considerations for graft choice in anterior cruciate ligament reconstruction

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Abstract: Injury to the anterior cruciate ligament (ACL) of the knee is common and often requires surgical reconstruction. There are numerous graft options available to the operating surgeon, to each of which a growing body of dedicated literature exists. Each of these potential choices of ACL graft specimen has a distinctive set of biomechanical properties, clinical outcome profiles, and other special considerations (e.g., autograft versus allograft, harvest site factors, and operating time). The purpose of this review is to discuss the biomechanical characteristics of the native ACL alongside those of several of the most commonly used ACL graft specimens based on a current review of the biomechanical literature. In doing so, this review will also briefly discuss the biomechanical implications for allograft versus autograft usage and single-bundle versus double-bundle repair techniques. This review lists and discusses the stress, strain, stiffness, Young's modulus, and ultimate load to failure of the native ACL, several common autografts [patellar bone-tendon-bone (BTB), hamstring tendon (HT), and quadriceps tendon (QT)], and several common allografts. Given the important biomechanical role of the ACL in stabilizing the knee to translational and rotational forces, it is crucial that the operating surgeon make a decision on graft choice that is informed in the biomechanical implications of ACL graft selection.

Keywords: Anterior cruciate ligament (ACL); reconstruction; autograft; allograft; biomechanics

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Introduction

Background

Injury to the anterior cruciate ligament (ACL) of the knee resulting in partial or complete tear is common especially in sporting activities and with movements that involve pivoting on the planted foot (1-3). Despite possessing a documented vascular supply, the ACL has minimal healing capacity even when only partially injured, and surgical reconstruction remains the standard of care, especially in patients who are young and/or active (4,5). ACL reconstruction (ACLR) is a common and successful procedure, with anywhere from 60,000 to 175,000 ACLRs being performed annually in the United States and over 90% of cases delivering good or excellent patient outcomes (1,6-8). The chief goal of ACLR is to restore biomechanical and kinematic function to the knee that approximates that of the knee in its native state (6,9,10).

The topic of optimal graft specimen selection remains a subject of ongoing debate (3,11). There exists a relatively wide range of graft choices [e.g., bone patellar-tendon bone (BTB), hamstring tendon (HT), quadriceps tendon (QT) with or without bone block] and configurations (e.g., autograft versus allograft, central tendon *vs.* lateral tendon

BTB, etc.). While concrete evidence currently exists for choosing some graft types/configurations over others, for many patients, the optimal choice of graft specimen remains a case-by-case decision which is decided upon by weighing the pros and cons of grafts with patient demographics and special circumstances. Many of these graft specimen-specific factors exist outside the scope of this review on the biomechanical considerations of ACL graft choices (e.g., harvest site pain, patient activity level, post-operative rehabilitation, patient's personal preferences, etc.) (11).

General biomechanical considerations in graft selection

The structure of a graft is inherently related to its material properties on both the macro- and microscopic levels. This review will therefore focus heavily on the anatomical and histological properties of the native ACL and several common graft choices along with their individual material properties. "Material properties" can be further subdivided into "mechanical" and "structural" properties (12). The former relates to the composition of a structure (e.g., the organization and amount of collagen present, its dimensions, etc.) and the later relates to how the structure (i.e., ligament or graft) functions when in sit (12).

Matching the anatomical and biomechanical properties of an ACL graft with the native ACL is important for minimizing the risk of ACL graft failure (13-16). A study by Thein *et al.* comparing the anatomical footprint of the native ACL to anatomically-placed BTB grafts (i.e., controlling for graft course through the knee) found these grafts to be, on average, larger in cross-sectional area (CSA) and to experience impingement at higher rates compared to the native ACL (a pathological phenomenon associated with higher rates of graft failure) (17). Meanwhile, a study by Offerhaus *et al.* found that the CSA of BTB autografts tend to be smaller than that of the native ACL, whereas HT autografts tend to be oversized in terms of their CSA compared to the native state (16).

Beyond the geometric properties of ACL grafts, the material properties of a given graft also provide crucial considerations for ACL graft selection. Baer *et al.* describes the biological and immunological process of graft incorporation following fixation, noting that the later stages of this process render graft material, on average, with lower tensile strength than prior to fixation (18). It should therefore go without saying that choosing grafts with suitable mechanical properties prior to fixation is critical to reducing a patient's chances of graft failure and maximizing a patient's likelihood for enjoying a good or excellent functional outcome.

Rationale and knowledge gap

Whereas other studies on this topic have primarily focused on outcome-based considerations in the discussion of optimal graft choice in ACLR, this review will focus solely on the comparative biomechanical considerations for the most common graft choices, as a substantial body of literature already exists to compare the outcomes observed for the various graft options. There are numerous studies that describe the biomechanical properties of the various ACL graft specimens, including several systematic reviews which directly compare different graft specimens. However, no studies currently exist to discuss these findings cumulatively in the context of other important biomechanical considerations for graft choice. These topics include graft source (i.e., whether a graft is taken from an autologous or cadaveric source) how graft diameter may affect strength and risk for impingement and subsequent failure, and the impact of single- versus double-bundle reconstruction techniques.

Objective

Our objective is to review the pertinent biomechanical metrics of several of the most commonly used graft specimens for ACLR in the context of other biomechanically relevant topics critical to ACLR. We aim to do so by first reviewing the biomechanical properties of the native ACL and its function in stabilizing the knee. The discussion will then turn to biomechanical considerations for choosing autografts versus their allograft counterparts. Next, several of the most common graft types will be individually discussed in terms of their distinctive mechanical properties. This discussion will also make note of the currently understood biomechanical considerations for single- and double-bundle ACLR techniques.

Discussion

Biomechanical properties of the native ACL

The ACL mainly functions to stabilize the knee against anterior translation of the tibia against the femur (4,5,13,19,20). At 30 degrees of knee flexion, the ACL resists 82–89% of anteriorly-applied load to the knee, and this proportion decreases slightly to 74–85% when flexion of the knee is increased to 90 degrees (5,19,20). Secondarily, the ACL stabilizes the knee against varus forces, internally- and externally-directed rotational torques on the knee, and aids in the prevention knee hyperextension, especially during locomotion (4,13,19,21).

Owing to the slightly opposed courses taken by the two composite bundles of the ACL, the ligament remains under some degree of tension throughout the knee's normal range of motion with the anteromedial (AM) bundle experiencing tension during knee flexion and the posterolateral (PL) bundle experiencing tension during knee extension (19,22). The amount of tension experienced by the ligament, as well as by each individual bundle relative to one another, is dynamic and varies with knee position (13). During extension, the two bundles of the ACL experience some degree of rotation around each other as the ligament itself is torqued slightly about its longitudinal axis such that the AM bundle appears to wrap around the PL bundle (5). It is the predominance of the PL bundle's role in countering translational forces in the extended knee that has provided the rationale for pursuing investigations of double-bundle reconstruction techniques (5).

Cadaveric studies have largely demonstrated that the highest tensile forces experienced by the ACL occur at flexion angles under 30 degrees for a wide range of applied loads, including rotational torque, translational forces, and varus/valgus loads (22,23). In a cadaveric study performed by Markolf *et al.*, the highest achievable tensile force on the native ACL was achieved in hyperextension (−5 degrees) with a 100 N anterior force applied concomitantly with a 10 Nm internally-directed torque on the knee (23). The stress-strain characteristics of the native ACL are influenced by multiple structural and ultrastructural characteristics. The crimping pattern of the collagen bundles of the ACL has been shown to explain the characteristic three-phase stress-strain plot of the ACL (22). Biomechanical studies of the isolated ACL have shown it to have a variable tensile and mechanical behavior that is strain-rate dependent (22). It has been shown to have a maximum tolerable load and strain to maximum load that are positively correlated with increasing strain rate (22).

An important distinction in the biomechanical literature exists between whether the ACL is studied as a standalone ligamentous specimen, or, as it has been noted to function in situ, as a complex with its surrounding bony insertions, being referred to as the femur-ACL-tibia complex (FATC) (12,13,22,24). A study performed by Woo *et al.* of this complex in 1991 found the ultimate load strength of this complex to be 2,160 N (±157 N), a reference value used by an impressive corpus of literature following this study's finding (24). Biomechanical investigations of the tensile and mechanical properties of the native ACL and the available graft choices have focused on both the ligaments as standalone structures and as a complex with their surrounding bony attachments, but debate remains about the degree of translatability of data gained from studies of the ACL and various graft options as standalone structures to their actual *in situ* characteristics and performance.

The native ACL, like other ligaments around the body, is a viscoelastic structure (22). Its maximum tensile strength (load to failure) in young specimens has been estimated by several biomechanical studies and has found to be approximately 2,160 N, with estimates ranging as high as 2,300 N (5,18,19,22,24-26). A review performed by Hassebrock *et al.* suggested that the AM bundle may have slightly higher stress and strain characteristics than the PL bundle (19). Its estimated linear stiffness has been estimated to be approximately 242 N/mm (5,24). It should be noted that patient sex and age play a role in determining the tensile and mechanical characteristics of the native ACL, both due to the constitution makeup of the ACL, as well as the magnitude and directionality of the forces experienced by the native ACL in various demographic groups (24). As age increases, the estimated load to failure and stiffness for the native ACL has been shown to significantly decrease from the values listed above, down to an estimated load to failure of 658 N and stiffness of 180 N/mm (specimens aged 60–97 years) (5).

Allografts versus autografts

There exists an array of factors that allow for comparison of allografts and autografts, such as donor site morbidity, cost, and operation time (1,18,21,25,27), however many of these considerations fall outside of the scope of this review in which the biomechanical considerations between different graft choices are made the chief focus. Little data exists to examine the biomechanical and structural changes that take place within allografts after being present *in vivo* for enough time for the immune system and local biomechanical stresses to have an effect on the structural integrity of these grafts (18). One measure that serves as somewhat of a proxy for the biomechanical integrity of an *in vivo* graft is its failure rate. Of course, factors beyond the structural integrity of the graft, such as tibial slope, tunnel position, etc., also influence failure rate significantly, which is why

Table 1 Table summarizing key findings on the material properties of the various ACL autograft options discussed in this section

Graft type	Graft source	Cross-sectional area (mm^2)	Youngs modulus (MPa)	Stiffness (N/mm)	Tensile strength (N)	Studies
Autograft	Patellar bone-tendon-bone	48.4	225–337.8	210–278	1,581 to 1,784	Wilson *et al.* 1999, Shani *et al.* 2016
Autograft	Hamstring tendon	57	154	238	2,422	Zantop *et al.* 2006, Pearsall *et al.* 2003
Autograft	Quadriceps tendon	91.2	255.3	466	2,186	Baawa-Ameyaw *et al.* 2021, and Sasaki *et al.* 2014

ACL, anterior cruciate ligament.

failure rate can only serve as a proxy (28,29).

Studies have documented anywhere from a 3- to 5-time higher failure rate of allografts compared to autografts (10,21,30,31). In large part, this is why allografts are often reserved for revision cases in which autograft harvesting is complicated or not possible, or for elderly patients, a demographic group in which graft failure is all-around less likely (10,21,30,31). With this being said, it has been well documented that patients receiving allografts for ACLR can achieve excellent outcomes at comparable rates to those undergoing the same procedure with autografting (18).

Debate exists about the effect of sterilization method on allograft integrity. Chahal *et al.* found that the method of allograft sterilization did not have a significant effect on the revision rate of ACLR performed with allografts (7). Some studies have failed to find a significant difference in revision rates between ACLR performed with allografts and those performed with autografts with allograft sterilization method having no clear impact on this finding (7,32).

Counter to this, Mariscalco *et al.* asserted that irradiated allografts have a higher failure rate compared to equivalent autografts. Furthermore, they found that nonirradiated allografts had a failure rate that was not significantly different from autografts, implying that the method of graft sterilization could, in fact, have a profound effect on allograft integrity (10). Donor factors can also affect the biomechanical integrity of autografts. For instance, age explains a significant proportion of mechanical differences between allograft samples, with increasing donor age being correlated with inferior mechanical properties of graft specimens (33,34).

Graft type

Patellar bone-tendon-bone (BTB) autograft

Often thought to be the gold standard for ACL graft choices, the patellar BTB graft is one of the most commonly chosen grafts for ACLR (1,12,30). In young, active patients, especially those who are athletes, the BTB graft continues to be regarded as one of the best options for primary ACLR due to its well-documented low failure rate in this group, especially in comparison to hamstring grafts, as well as for its comparatively lower post-operative residual laxity and instability (30). While it is unclear whether or not cross-sectional area affects graft strength directly, increasing BTB graft length is correlated with increased tensile strength (21,25). Biomechanical studies have helped establish the mechanical superiority of using the central third of the bone-patellar tendon-bone complex rather than one half (a "hemi-BTB graft" as it has been called in the literature), and so central third BTB grafts have become almost synonymous with the simple term "BTB graft" (35).

The material properties of the BTB graft have been measured multiple studies. It has been described to have an average CSA of 48.4 mm^2, average ultimate stress of 33.4 MPa, ultimate strain of 11.4%, Youngs modulus of 225 to 337.8 MPa, stiffness of 210 to 278 N/mm, and a maximum load to failure (tensile strength) of 1,581 to 1,784 N (11-13,25) (*Table 1*). Wilson *et al.* reported that augmenting the osseous components at their attachment sites with methyl methacrylate and cement caused them to fail more frequently at their midsubstance rather than at the bony ends of attachment (11). A biomechanical study by Cooper *et al.* reported much higher average loads to failure for BTB grafts than was previously described (4,389 N for a 15 mm graft), even after taking into account the increased length of BTB graft specimens that were studied (36). Furthermore, the authors found that rotating the graft 90 degrees offered further strength benefits (36).

HT autograft

There are several different types of hamstring-based grafts that are commonly used in ACLR, but this review will mostly focus on the gracilis and semitendinosus quadrupled graft (GST4), which is a four-stranded graft made from the semitendinosus and gracilis tendons and associated muscle (37). Graft diameter and length are two important variables in hamstring autograft that have biomechanical consequences. HT graft diameter has been shown to be positively correlated with increasing patient height but not with increasing patient body mass index (21). A 2015 study performed by Boniello *et al.* reported that increasing HT graft diameter was directly correlated with increased graft strength, although they concede that the grafts tested demonstrated significant variability in their apparent maximum load to failure (38). Alomar *et al.* demonstrated that HT grafts with diameters greater than 7 mm displayed significantly superior tensile properties compared to those with smaller diameters (39).

Graft length has been found to be predictive of tensile properties, especially when paired with numerous patient characteristics including; height, gender and ethnicity (40). Length is also an important factor for determining the manner in which grafts can be tested *in vitro*, as it directly affects ability to perform different graft preparation techniques, i.e., quadrupled semitendinosus (ST4), the GST4, and versus tripled constructs. Pailhe *et al.* demonstrated ST4 had the highest maximum load to failure when compared with GST4 or a quadrupled gracilis (G4). However, a length of >28 cm is usually needed for a ST4 autograft, and in some patient populations (e.g., female), 43.8% of patients have ST graft lengths of <28 cm. Furthermore, a tripled ST (ST3) construct has been shown to be markedly biomechanically inferior to four stranded constructs. Hence, the most reliable four-stranded construct available is often the GST4 (41).

The material properties of the HT graft have been measured multiple studies. It has been described to have an average CSA of 57 mm^2, Youngs modulus 154 MPa, and stiffness of 238 N/mm (11). The maximum load to failure (tensile strength) of the HT graft has been reported by multiple studies to be higher than that of the native ACL, with 2,422 N being the commonly-cited value, and other estimates ranging as high as 4,500 N (11,25,42).

Several studies have failed to show a difference in the functional outcomes for patients undergoing ACLR and receiving HT grafts versus those receiving BTB grafts (11,43). However, when it comes to failure rates, the overwhelming literary consensus is that HT grafts in younger and more active patient populations experience significantly higher rates of graft failure in comparison to those within the same demographic groups who receive BTB grafts (1,21,30). This is counterintuitive when considering the higher reported values aforementioned for hamstring tensile strength in comparison to BTB grafts and the native ACL (44). Nevertheless, Barrett *et al.* supports this consensus on the preferable failure profile of BTB grafts in young patients, while also finding that hamstring grafts have a significantly lower failure rate in older demographics, although there exists less consensus about this latter point (1). All of the data on comparative failure rates of ACL graft choices should consider the fact that all graft types appear to have a higher failure rate in younger, more active patients (1).

QT autograft

The QT autograft is harvested from the central component of the QT and contains terminal fibers from the vastus medialis and intermedius muscles along with the rectus femoris (21), The QT graft is a usually a bilaminar, although can be trilaminar or quadrilaminar, graft option that is a more modular graft choice in comparison to those that have already been discussed, especially given that it can be harvested with or without bone plugs (21,30). While it has grown in popularity in recent years, it remains a less common choice in comparison to the two aforementioned options (21,30).

QT grafts have been noted to have larger CSA on average when compared to BTB autografts (12). Full-thickness QT grafts have nearly two times more cross-sectional area than BTBs on average, and furthermore, tend to possess a higher tensile strength (3,12,30,45). To the best of our knowledge, no studies exist to determine if the increased cross-sectional area of QT grafts effect the rate of QT graft impingement. As with other previously discussed graft choices, the material properties of the QT graft have been described by various studies. The QT graft has been found to have an ultimate stress of 23.9 MPa, strain of 10.7%, Youngs modulus of 255.3 MPa ultimate load to failure for QT grafts of 2,186 N and a stiffness of

Table 2 Table summarizing key findings on the material properties of the various ACL allograft options discussed in this section

Graft type	Graft source	Cross-sectional area (mm^2)	Stiffness (N/mm)	Tensile strength (N)	Studies
Allograft	Patellar bone-tendon-bone	35	168 to 620	1,139 to 2,977	Baer *et al.* 2007
Allograft	Hamstring tendon	53	776	4,090	Almqvist *et al.* 2007
Allograft	Tibialis anterior	48.2	460	4,122	
Allograft	Tibialis posterior	44.4	379	3,594	
Allograft	Achilles tendon	67	685	4,617	

ACL, anterior cruciate ligament.

466 N/mm, both of which are higher than what has been described for BTB grafts (12,46). While QT grafts tend have a wider CSA (91.2 mm^2) than BTBs on average, a wider QT graft may not necessarily be requisite for achieving increased tensile strength. For instance, a systematic review by Mouarbes *et al.* noted that QT grafts have been found to exhibit a 1.36-time greater load to failure than BTB grafts of a similar width (3,12). The higher tensile strength of QT grafts likely relates to their distinct histological differences from other graft types, namely the increased collagen (around 20% more than comparable BTB grafts), larger fibroblast density and increased fibril-interstitial ratio of QT grafts in comparison to BTB grafts (3,46).

As previously alluded to there are multiple different QT graft harvest techniques which include both full and partial thickness options, as well as options that are all soft tissue, or those that include a bone block. There is very limited data available regarding biomechanical comparison of partial versus full thickness QT autografts. There is a recent systematic review which assessed clinical outcomes and complications and found there to be no significant differences in outcome or complications (45,47). Strauss *et al.* did assess biomechanical properties of quad tendon grafts with and without a bone block and compared these with gold standard grafts such as BTB and ST4. They found only the full thickness QT with a bone block had similar biomechanical properties to BTB and ST4. However, a recent systematic review found no difference in graft rupture between QT with a bone block versus all soft tissue. Therefore further biomechanical and clinical data is needed to further draw conclusions on superiority of different types of QT autograft (48).

Common allografts

A variety of allografts exist and are commonly employed in ACLR (*Table 2*). The available allografts that will be discussed in this review in terms of their biomechanical properties include allograft variants of the previously discussed autografts (BTB and HT allografts), as well as several other grafts including the doubled tibialis anterior (TA) allograft, doubled tibialis posterior (TP) allograft, and Achilles tendon (AT) allograft. The BTB allograft has been found to have an average CSA of 35 mm^2, stiffness of 168 to 620 N/mm, and ultimate load to failure of 1,139 to 2,977 N (18,49). The HT allograft has been found to have an average CSA of 53 mm^2, stiffness of 776 N/mm, and ultimate load to failure of 4,090 N (18). Almqvist *et al.* did not find a consistent pattern among or across the different groups of graft types studied in terms of where failure occurred along the length of the graft (49).

The TA allograft has been found to have an average CSA of 48.2 mm^2, stiffness of 460 N/mm, and ultimate load to failure of 4,122 N (18). The TP allograft has been found to have an average CSA of 44.4 mm^2, stiffness of 379 N/mm, and ultimate load to failure of 3,594 N (18). The AT allograft has been found to have an average CSA of 67 mm^2, stiffness of 685 N/mm, and ultimate load to failure of 4,617 N (18). Care must be taken when attempting to directly compare biomechanical models of the mechanical properties of grafts because differences in mechanisms by which grafts are placed under tension and tested can greatly affected the observed biomechanical values between trials (49).

Double- versus single-bundle reconstruction

Despite a considerable amount of literature analyzing and discussing the differences between single-bundle and double-bundle ACLR techniques, it remains relatively unclear which method is superior (4,50). While some studies have simply failed to display a biomechanical difference between the two techniques (51), it is at least of general literary consensus that both repair methods have overlapping benefits, while also each having distinct superiorities and drawbacks. Single-bundle repairs have been shown to restore biomechanical function in postoperative pivot shift tests with regard to displacement and rotation when repair replicates the AM bundle (4). A cadaveric study by Markolf *et al.* using a biomechanical model to compare single- and double-bundle ACLR found single bundle reconstructions to be the superior method for restoring kinematic knee properties and periarticular stability as closely to the native state as possible, as measured by graft forces, knee laxities, and tibial rotation (23).

Meanwhile, Yagi *et al.* performed a biomechanical analysis of ACLR and found anatomic (double-bundle) reconstruction to be far superior than single-bundle reconstruction at restoring the knee's ability to resist anterior tibial translation (8). With this being said, repairs with a double-bundle graft have also been shown to result in higher forces across the graft which may contribute to graft failure; however, some biomechanical investigations have suggested that double-bundle repairs result in a more kinematically accurate repair (Kraeutler *et al.*) and Tsai *et al.*, especially for restoring rotational stability of the knee (4,52).

Limitations

This review, while adding to the ongoing discussion regarding the biomechanical considerations of graft choice in ACLR, is not without its limitations. The authors analyze the findings of a large number of studies contributing to a common topic, but this is not a systematic review and is not intended to be interpreted as such. This study is purely a review article and therefore some subjectivity of the authors exists in determining which articles present pertinent enough information to discuss. While a significant focus was made to include studies that are well-incorporated into the current literature and systematic reviews on this subject that preexist this article, some subjectivity in article selection inevitably remains, as is the case for all review articles of this nature. Therefore, it should be noted that this review does not have the methods or statistical power to make determinations on the statistical significance of differences between various biomechanical metrics presented in different studies.

Conclusions

A thorough review of the biomechanical literature would yield numerous options and techniques for ACLR that provide satisfactory biomechanical outcomes at time zero. However, the biomechanical literature is notably deficient in data that describes long term outcomes and clinical implications for biological healing and plastic deformation of different graft specimens. Therefore, more studies assessing the long-term biomechanical outcomes of these grafts would greatly augment the current literature. Furthermore, there is a relative sparsity of literature regarding less common graft options such as peroneus longus, which should receive further investigation in future studies. Given the relative equivalence of the different autograft types from a biomechanical standpoint in the currently available literature, it is the senior author's preferred technique to utilize the following graft types in the following order, assuming they are all available options without other underlying pathologies: BTB, QT and HT. Allografts are an acceptable option in revision cases, patients not returning to pivoting sports, or patients over 40 years of age. Future studies are needed to further define the relationship between cross-sectional area of these different graft options and their likelihood of failure, as well as how to maximize cross-sectional area for improved strength within this context.

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