Replication of the Range of Native Anterior Cruciate Ligament Fiber Length Change Behavior Achieved by Different Grafts


James Robinson,*† FRCS(Orth), MS, Fatima Cody Stanford,‡ MD, Daniel Kendoff,‡ MD, Volker Stüber,‡ MD, and Andrew Pearle,‡ MD

From the †Avon Orthopaedic Centre, Bristol, United Kingdom, and ‡Sports Medicine and Shoulder Service, Hospital for Special Surgery, New York City, New York

Background: The native anterior cruciate ligament (ACL) does not behave as a simple bundle of fibers with constant tension but as a continuum of ligament fibers with differential length change during knee flexion/extension. Computer-assisted navigation can be used to assess length change in different fibers within the native ACL and to evaluate how different reconstruction grafts replicate the range of native ligament fiber length change behavior.

Hypothesis: Anterior cruciate ligament reconstruction graft size and configuration (single- vs double-bundle) are deciding factors as to how much of the native ACL fiber length change behavior is replicated.

Study Design: Controlled laboratory study

Methods: The fiber length change behavior of the entire native ACL was assessed by measuring the length change pattern of representative anteromedial (AM) and posterolateral (PL) bundle fibers (1 at the center and 4 at the periphery of each bundle). The tibial and femoral ACL attachment areas in 5 fresh-frozen cadaveric knees were digitized, and the length change of each representative fiber was recorded during knee flexion/extension using an image-free, optical navigation system. Subsequently, single-bundle ACL reconstructions of different diameters (6, 9, and 12 mm) positioned at the center of the overall native femoral and tibial attachment sites were modeled to assess how much of the range of ligament fiber length change of the native ligament was captured. This was compared with a double-bundle graft using 6-mm-diameter AM and PL grafts positioned at the centers of the femoral and tibial attachment sites of each separate bundle.

Results: The 6-, 9-, and 12-mm single-bundle grafts simulated 32%, 51%, and 66% of the ligament fiber length change behavior of the native ACL, respectively. The length change patterns in these grafts were similar to the central fibers of the native ACL: the PL fibers of the AM bundle and AM fibers of the PL bundle. However, even a 12-mm graft did not represent the most AM and PL native fibers. The 6-mm AM and PL bundle grafts (equivalent in cross-sectional area to a 9-mm single-bundle graft) simulated 71% of the native ACL and better captured the extremes of the range of native ligament fiber length change.

Conclusion: Increasing single-bundle graft size appears to capture more of the range of native ACL fiber length change. However, for a similar graft cross-sectional area, a 2-bundle graft simulates the length change behavior of the native ligament more precisely and thus may better emulate the synergistic actions of anisometric and isometric fibers of the native ligament in restraining knee laxity throughout the range of flexion.

Clinical Relevance: The range of native ACL fiber length change behavior is better replicated by larger diameter grafts but may be best reproduced by double-bundle reconstruction.

Keywords: anterior cruciate ligament; double bundle; isometry; fiber length change

*Address correspondence to James Robinson, FRCS(Orth), MS, Avon Orthopaedic Centre, Southmead Hospital, Westbury-on-Trym, Bristol, BS10 5NB, UK (e-mail: james.robinson@nbt.nhs.uk).

No potential conflict of interest declared.
flexion. Although Odensten and Gillquist\textsuperscript{17} found no histological evidence to separate the ligament into distinct components, as a basis to better understand its restraining function, anteromedial (AM) and posterolateral (PL) fiber bundles have been described. The AM bundle fibers have been shown to undergo small length changes from full extension to 90° of flexion, whereas the PL bundle fibers demonstrate large changes in length from full extension to 90° of flexion.\textsuperscript{6,19,24,26} The AM and PL bundles act synergistically to restrain anterior laxity throughout the range of knee flexion, with the PL bundle fibers providing the more important restraint to anterior laxity near extension as opposed to flexion, when it is slack. In addition, the obliquity of the PL bundle is thought to better restrain tibial rotation.\textsuperscript{21}

Both in vitro\textsuperscript{15,25} and in vivo studies\textsuperscript{21} have suggested that double-bundle ACL reconstruction grafts can replicate the function of the native ligament more effectively than a single-bundle ACL graft. Improvements in both anterior translation and rotation control have been demonstrated.\textsuperscript{15,25} In addition, it has been suggested that the larger “footprint” of double-bundle reconstructions may also improve graft healing at the tunnel apertures due to an increase in the bone tunnel–graft interface.\textsuperscript{9} However, despite the advantages that have been shown in the above studies, double-bundle reconstructions have only resulted in improved outcomes in some clinical trials\textsuperscript{13} and not others.\textsuperscript{1} The argument persists that a well-placed single-bundle ACL graft replicates enough of the biomechanical behavior of the native ACL to sufficiently restore anterior laxity and tibial rotation to allow patients to return to sports.

Although studies have investigated the dimensions for the native ACL,\textsuperscript{5,7,10,11,16,21,23} it is still unclear how much of the surface area of the anatomical insertion a reconstruction graft must fill to reproduce normal ACL function. To date, there are no volumetric analyses that can be used to understand the percentage of volumetric fill of different-sized single- or double-bundle ACL grafts. In addition, it is unknown how much of the normal length tension behavior of the normal ACL is reproduced by ACL reconstruction grafts. Previous studies have examined the length change behavior of a single-bundle ACL graft centered at the femoral and tibial AM bundle insertion sites.\textsuperscript{20} Computer-assisted navigation software now allows the study of the length change behavior of multiple fibers in both the native ligament and in modeled ACL reconstruction grafts. Thus the range of fiber length change behavior of the native ACL may be compared with that of a single- or double-bundle ACL reconstruction graft. This provides some insight into the functional portion of the native ACL that is restored with the reconstruction.

The goals of this study were to (1) determine the percentage of the native femoral and tibial attachment sites that are filled by different-sized ACL reconstructive grafts, (2) determine the range of ligament fiber length change behavior for the native ACL, and (3) measure the range of native AM and PL bundle fiber length changes replicated by different-sized single-bundle ACL grafts, positioned at the overall center of the native attachment areas, compared with a double-bundle ACL graft with the AM graft positioned at the centers of the AM bundle attachment sites and the PL graft positioned at the centers of the PL bundle attachment sites.

**Materials and Methods**

This study was performed on 5 fresh-frozen human cadaveric lower limbs (age range, 25-44 years; 3 male and 2 female) that were obtained under a protocol approved by the local research ethics committee. Specimens were prepared by removal of soft tissues so that they could be bench mounted, using a vise secured around the proximal femur, allowing knee flexion from 0° to 90°. Physical examination and arthroscopy of the knee were performed to ensure ligamentous integrity and absence of degenerative disease. Knees with surgical scars, ACL rupture, or significant osteoarthritis were excluded.

A Surgetics computer-assisted navigation station (PRAXIM Medivision, La Tronche, France) was used in this study for data acquisition. The accuracy of this system has previously been validated, showing a near-perfect correlation between the surgical navigation measurements and those made by a robotic/universal force moment sensor (UFS) testing system (seen as the gold standard for measurement) in a clinically relevant model.\textsuperscript{18} Tibial and femoral rigid body navigation arrays were fixed to their corresponding bones. After calibration and registration, the tibial and femoral ACL attachment areas were digitized by Bone Morphing (PRAXIM Medivision) using an arthroscopic navigation probe equipped with optical markers. During this process 50 to 100 reference points on each respective surface were captured, allowing the navigation software to adapt a standard knee model to the 3-dimensional (3-D) anatomy of the individual knee. The registration process was completed by performing a flexion/extension kinematic examination. The recorded motion of the tibia and femur during this examination, performed with the ACL intact, served as the kinematic model for the post hoc analysis of fiber length change of both the native ACL bundles and the ACL reconstruction grafts. Thus potential kinematic discrepancies between the ACL-intact and ACL-deficient knee were avoided.

A medial parapatellar arthrotomy was performed and the synovial covering of the ACL carefully removed. By flexing and extending the knee, the AM and PL bundles could be distinguished, and a probe was bluntly placed between them. The ACL was transected then at this level, and tagging sutures were placed in each bundle. Traction of each sutures, tensioning the respective bundle, permitted differentiation of their distinct attachment sites. The tibial and femoral footprints were marked with a Bovie electrocautery and detailed bone morphing of the footprints performed.\textsuperscript{18} The software calculated the surface area of the attachments, and a mean of the 5 specimens was taken.

**Determining the Range of Fiber Length Change for the Native ACL**

The effect of knee flexion/extension on the lengths of various fibers was determined using the Surgetics “Fiber Function” software (PRAXIM Medivision). The use of this
software to measure fiber length change behavior during ACL reconstruction has been previously described. The change in length between a digitized point on the femoral ACL attachment site and a point on the tibial ACL attachment site is calculated as the knee is passively flexed and extended. To determine the range of fiber length change for the normal ACL, as the knee was passively flexed from 0° to 90°, we recorded the length change behavior of 10 representative fibers. The most anterior, the most posterior, the most medial, and the most lateral fibers of the AM and PL bundles (positions defined in the extended knee) were identified by inspection and their insertions at the femoral and tibial ACL attachment sites digitized. To define the centers of the AM and PL bundles, a post hoc analysis on our morphed, 3-D virtual model was performed using the Surgetics navigation software (PRAXIM Medivision). A software tool allowed for a best-fit circle to be constructed within the morphed AM and PL tibial and femoral attachment sites. The center of each circle defined the center of the bundle attachment site. The length change behavior of each of these fibers was displayed graphically in real time. The raw data were also imported into Microsoft Excel for analysis (Microsoft Corp, Seattle, Washington). For subsequent data analysis, fiber length was normalized to zero at full extension. The mean change in fiber length was calculated at 5° increments in knee flexion from 0° to 90° for each representative fiber for the 5 specimens.

Creation of Virtual Fibers and Grafts

The Surgetics navigation software (PRAXIM Medivision) was used to create virtual ACL reconstruction grafts in each knee. To define the center of the native tibial and femoral ACL attachment sites, the entire morphed ACL footprints were analyzed and best-fit circles applied using the software tool. The center of this circle defined the center native attachment site and was the position selected for the central fiber of the single-bundle ACL reconstruction grafts. Similarly, for the double-bundle grafts, the central fiber of each graft was positioned at the previously defined center of native AM and PL attachments, respectively.

Single-bundle virtual ACL grafts of 6, 9, and 12 mm in diameter were sequentially created. The central fiber of these grafts was located at the center of the native ligament attachment area as determined by the navigation software. For each ACL graft, the percentage of the coverage of the native attachment sites was calculated and the range of ACL graft fiber length changes measured. The percentage of the fill of the native attachment area by each graft was then calculated as the following: area of the graft footprint / (area of native ACL native attachment × 100).

The ligament fiber length change behavior of each graft with passive knee flexion from 0° to 90° was then assessed. As with the native ACL, we calculated the fiber length change profiles of the most anterior, posterior, medial, and lateral and the central fibers of the virtual grafts. We then compared the range of fiber length change of each graft with that of the native ligament.

To compare how a double-bundle ACL graft replicated the range of ligament fiber length change of the native ligament, 6-mm AM and 6-mm PL virtual grafts were created, with the position of their central fibers placed at the center of the native AM and PL bundles, respectively (as defined by the navigation post hoc analysis). The cross-sectional area of two 6-mm grafts is 56.6 mm² and is similar to that of a 9-mm-diameter single-bundle graft (63.6 mm²). It was hypothesized that this test was equivalent to comparing a single-bundle reconstruction technique with a double-bundle technique using similar graft material. The percentage of the fill of the native attachment area by these grafts was then calculated by the method described above. The fiber length change behavior of each graft was also assessed.

RESULTS

Anatomical Insertion Site Fill

The tibial attachment area of the native ACL was 197 mm² (range, 156-225 mm²), and the average area of the native femoral attachment was 196 mm² (range, 145-228 mm²). A 6-mm single-bundle graft filled 14.7% (range, 12.6%-18.1%) and 14.9% (range, 12.4%-19.5%) of the native tibial and femoral footprints, respectively. This increased to 33.0% (range, 28.3%-40.8%) for the tibial and 33.4% (range, 27.9%-43.9%) of the femoral footprint with a 9-mm graft. For the 12-mm graft, the percentage of the fill was 58.7% (range, 50.3%-72.5%) for the tibia and 59.4% (range, 49.6%-78.0%) for the femur. For two 6-mm AM and PL grafts (equivalent to a 9-mm single-bundle graft), the percentage of the fill of the attachment areas was 29% (range, 25.1%-36.2%) and 30% (range, 24.8%-39.0%) for the tibia and femur, respectively.

Range of Ligament Fiber Length Changes

The average ligament fiber length change profiles for the representative fibers of the native ACL are shown in Figure 1. The central fiber of the AM bundle was relatively isometric during passive knee flexion (0°-90°). This fiber was slackest at 40° flexion with a mean length change of 1.7 mm (range, 0.6-2.3 mm). However, the most anterior fiber of the AM bundle tightened as the knee flexed from 0° to 90°. The distance between its femoral and tibial attachments progressively increased by 3.6 mm (range, 2.3-5.7 mm) at 90°. Conversely, the most posterior AM bundle fiber slackened with flexion. The distance between the femoral and tibial attachments diminished by 4.9 mm (range, 3.7-6.0 mm) at 90°.

The PL bundle was relatively anisometric with all representative fibers slackening as the knee flexed from 0° to 90°. The distance between the tibial and femoral attachments of the central fiber increased by 7.8 mm (range, 5.6-10 mm). The most anterior PL bundle fiber was slackest at 40° of flexion with the distance between the attachments decreasing by 4.1 mm (range, 2.8-5.5 mm). The most posterior PL bundle fiber was the most anisometric, slackening rapidly with knee flexion. The distance between its femoral and tibial attachments decreased by 11 mm (range, 8.7-13.1 mm) at 90° of flexion.
The ligament fiber length change profiles for the modeled single-bundle reconstruction grafts are shown in Figure 2. The central fibers of these grafts exhibited 5.6 mm of length change between 0° and 90° of flexion. The 6-mm-diameter graft captured 32% (range, 25.3%-35.0%) of the range of fiber length change of the native ligament. The range of fiber length change was similar to that of the posterior fibers of the native AM bundle and the AM fibers of the native PL bundle. Increasing the diameter of the graft to 9 mm captured 51% (range, 40.4%-55.9%) of the length change behavior of the normal ACL with the graft additionally capturing the behavior of the lateral fibers of the AM bundle and the central and medial fibers of the PL bundle. Further increasing the size of the single-bundle graft to 12 mm in diameter increased the percentage of capture of the native ACL to 66% (range, 52.8%-71.1%), additionally incorporating the central AM bundle fibers and the lateral PL bundle fibers. Only the most anteromedial AM bundle fibers and the most posterolateral PL bundle fibers were not represented by this graft.

The range of fiber length change of the two 6-mm double-bundle ACL reconstruction grafts represented 71% (range, 56.4%-78.0%) of the native ACL. The central portion of the native ACL, namely the PL fibers of the AM bundle and the AM fibers of the native PL bundle, was not represented.

**DISCUSSION**

The native ACL is a complex structure and may be thought of as a continuum of ligament fibers. Using histological analysis, Odensten and Gillquist did not find evidence to support the division of the ACL into distinct fiber bundles. However, studies of fetal development have demonstrated 2 bundles of fibers, and much of the recent literature has distinguished AM and PL bundles as a basis for understanding the function of the ligament. The synergistic load-sharing function of the bundles is well known. Previous studies have assessed fiber length change behavior in different portions of the ligament using narrow gauge wires attached to the centers of the ligament bundles in vitro or with magnetic resonance imaging in vivo. However, these studies have only measured the behavior of one fiber at the center of each bundle. The computer-assisted navigation system that we used in this study allows the measurement of length change behavior of any representative fiber within the native ligament.

Our study showed a similar tensioning pattern for the central fibers of the AM and PL bundles found in these previous studies. The central fiber of the AM bundle was relatively isometric, with a 2.3-mm length change as the knee flexed between 0° and 90°, compared with the more anisometric central fiber of the PL bundle that changed
5.6 mm in length through this range of motion. However, the length change profiles of the fibers at the periphery of the AM bundle did not exhibit uniform tensioning patterns. The most anterior and medial fibers of the AM bundle tightened with knee flexion; in contrast, the more lateral and posterior fibers slackened with flexion. All the PL bundle fibers slackened with knee flexion, with the most posterior fibers exhibiting the greatest length change. Thus, the native ACL behaves as a continuum of fibers with different length change behavior as the knee flexes and extends.

Although previous studies have sought to measure the surface area of the native ACL attachment site, few studies have measured the percentage of the native attachment site filled by a different size and configuration of ACL grafts. Ferretti et al used a laser 3-D digitizer camera to evaluate the ACL attachment site topography and determined that the surface area of the ACL femoral attachment was 196.8 ± 23.1 mm², with the AM and PL bundles contributing 120 ± 19 mm² and 76.8 ± 15 mm², respectively. We found a similar surface area for the femoral attachment (196.6 mm²), although these results differ from those of Harner et al who delineated the attachment areas with pen and ink. Our results suggest that only a small proportion of the native ACL footprint is filled by a centrally positioned single-bundle ACL reconstruction graft placed into the center of the native ACL attachments (14.7% and 14.9% of the tibial and femoral attachments, respectively, with a 6-mm graft; 33% and 33.4%, respectively, with a 9-mm graft). Despite this, a more significant proportion of the range of native ACL fiber length change was represented. A 6-mm bundle graft positioned at the center of the native ACL attachment sites replicates 32% of the range of native fiber length change, emulating the behavior of posterior fibers of the AM bundle and the anterior fibers of the PL bundle. Increasing the size of the graft to 9 mm further increases the representation to 51%, additionally incorporating the ACL fiber length change characteristics of the central and lateral AM bundle fibers and the medial and central PL bundle fibers. Rue et al have previously determined that orientating a transtibial, 10-mm femoral tunnel laterally, into the center of the native attachment area, allowed incorporation of 50% of the native AM bundle attachment and 51% of the PL, and it has been increasingly recognized by surgeons that moving the femoral tunnel placement for a single-bundle graft to a position lower on the lateral notch wall better captures the behavior of the more oblique PL bundle and may better control rotational stability.

The use of a 12-mm graft is, however, unlikely in the clinical setting. In addition, this size of graft risks intercondylar notch impingement, loss of knee extension, and “cyclops” lesions as the parallel fibers may lie too anterior in the region where the native ligament is curved. A 9-mm single-bundle graft is more representative of a large diameter 4-strand hamstring graft. With a similar amount of collagen, two 6-mm grafts could be fashioned. This graft configuration fills a similar percentage of the native anatomical attachment areas as a 9-mm single-bundle graft: 29% and 30% for the tibia and femur, respectively, with the double-bundle graft, compared with 33% and 33%, respectively, for the femoral footprint with the single-bundle 9-mm graft. Yet the double-bundle reconstruction captures 71% of the range of native ligament fiber length change compared with 51% with a centrally positioned single-bundle reconstruction (Figure 3). In addition, the double-bundle grafts better captured the diversity of the native ACL fiber length changes. The portion of the native ligament not represented by these grafts was the anterior fibers of the PL bundle and the posterior fibers of the AM bundle—the most central fibers of the native ACL. Some authors have identified an intermediate fiber bundle in this region whose behavior is similar to these fibers. Indeed some have advocated reconstructing it with a triple-bundle graft.

Our work is limited by the absence of load and muscle contraction forces acting across the joint. In addition, it has been suggested that isometric positions may change between the intact and reconstructed state. However, we applied a small posterior force to the knee during flexion/extension maneuvers to account for this, as has been previously described. The study has shown that computer-assisted navigation can provide data to both guide tunnel placement and also show the fiber length change characteristics of a proposed graft to help the surgeon determine which portion of the ACL isometric envelope they will reconstruct. We have demonstrated that a larger single-bundle ACL reconstruction graft, positioned at the center of the native attachment sites, will represent more of the native ACL fiber length change characteristics. However, a similar quantity of graft material split into a double-bundle reconstruction replicates a higher proportion of the native ACL fiber length changes and better represents native AM and PL bundle behavior.

REFERENCES