Biomechanical Comparison of Anatomic Single- and Double-Bundle Anterior Cruciate Ligament Reconstructions

An In Vitro Study

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Background: Arthroscopic identification of the anteromedial (AM) and posterolateral (PL) bundle locations of the anterior cruciate ligament (ACL) has facilitated an improved quantitative description of ACL anatomy. Few studies have directly compared the biomechanical laxity of anatomic single-bundle (SB) versus anatomic double-bundle (DB) ACL reconstruction techniques based on precise anatomic descriptions.

Hypothesis: Anatomic tunnel positioning for SB and DB reconstructions would produce comparable anterior-posterior and rotatory knee laxity.

Study Design: Controlled laboratory study.

Methods: Nine matched pairs of cadaveric knees were evaluated for the kinematics of intact, ACL-deficient, and either anatomic SB or anatomic DB ACL-reconstructed knees. Reconstruction tunnels were placed either centrally in the ACL footprint or within the AM and PL footprints. A 6 degrees of freedom robotic system was used to assess knee laxity with an 88-N anterior tibial load and a simulated pivot-shift test of combined 10-N·m valgus and 5-N·m internal tibial torques. Rotational motion was measured with internal and external torques of 5 N·m along with varus and valgus torques of 10 N·m. One-sample and 2-sample independent *t* tests were used to compare between groups ($P < .05$).

Results: No significant differences were found between anatomic SB and DB reconstruction groups during anterior tibial loading. Anterior tibial translations during simulated pivot shift had no significant differences between anatomic reconstruction groups. Tibial rotation for internal/external and varus/valgus torques showed no significant differences between anatomic reconstructions, with the exception of small (<3°) but statistically significant differences in internal rotation at 20° and 30° of flexion. Despite the similar behavior between the 2 anatomic reconstruction groups, neither technique was able to reproduce the intact state during an anterior tibial load.

Conclusion: No significant differences in anterior translation were found between the anatomic SB and anatomic DB ACL reconstructions for simulated pivot shift or anterior tibial loading.

Clinical Relevance: Although significant differences between reconstructions were observed for internal rotation, the small magnitude of these differences (<3°) may not have clinical significance.

Keywords: anterior cruciate ligament (ACL); anatomic ACL reconstruction; double-bundle; single-bundle; knee kinematics; pivot shift; robotics

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The native anterior cruciate ligament (ACL), whose complex anatomy is commonly described as being composed of 2 functional bundles,[19,32] plays an essential role in limiting tibiofemoral motion during dynamic knee movements.[10,47] The anteromedial (AM) and posterolateral (PL) bundles have been reported to have key roles in providing both anterior-posterior stability and rotational stability of the knee.[11,15,21] Precise arthroscopic identification of the AM and PL bundle locations has facilitated an improved quantitative description of overall ACL anatomy, which anatomic ACL reconstructions must replicate when aiming to restore native ACL function.[34,48]

Historically, single-bundle (SB) ACL reconstruction techniques have been reported to be successful in minimizing anterior translations and restoring the loading pattern of the ACL graft.[3,41] However, given a tendency to reconstruct primarily the AM bundle, because of its more central placement of the femoral tunnel in the intercondylar notch with transtibial femoral tunnel reaming, traditional SB

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ACL reconstructions reportedly remain insufficient in restoring internal/external and valgus rotations to physiologic levels.[18,35,40,41] Recent anatomic studies of the ACL have improved our understanding of the anatomic placement of the femoral and tibial tunnels relative to the transtibial SB reconstruction technique.[16,48] Additionally, these anatomic studies have resulted in a more anatomically accurate SB reconstruction attributable to modifications in femoral tunnel location with an anteromedial portal placement.[16,48] More recent double-bundle (DB) reconstruction methods aim to restore the native anatomy by addressing both bundles individually, which reportedly improves rotational knee laxity compared with SB reconstructions.[31,38,40,43,45] However, potential complications associated with the more complex DB reconstruction include notch impingement, inaccurate tunnel placement, increasingly difficult revision surgeries, intratunnel bone bridge fracturing, and increased expense.[4,6,7] An anatomic technique for SB ACL reconstruction aims to eliminate these complications by improving the tunnel placement of the conventional SB reconstruction based on recent quantitative anatomic studies of the ACL.[21,34,37,39,48]

It is still undetermined whether anatomic SB ACL reconstructions, which reconstruct the ACL with 1 bundle centrally located between the AM and PL bundle footprints, or DB ACL reconstructions, which reconstruct both the AM and PL bundles, better restore ACL-deficient knees to the intact state. Recent work has suggested that comparable results may be obtained with either an SB or a DB technique.[27] Anterior tibial translation alone is not correlated to functional clinical outcomes after ACL reconstruction, whereas rotational laxity has been correlated with subjective outcome measures of symptoms and knee function.[28]

The purpose of this study was to quantitatively measure knee laxity of anatomically reconstructed SB and DB ACLs in comparison with the intact and sectioned states in paired cadaveric specimens. We hypothesized that anatomic positioning of tunnels for both SB and DB reconstruction techniques would produce comparable anterior-posterior and rotatory knee laxity results.

MATERIALS AND METHODS

Specimen Preparation

Nine matched pairs of fresh-frozen, human cadaveric knees (6 bilateral male knees, 3 bilateral female knees; mean age, 46.7 years; SD, ±12.5 years; range, 16-58 years), without evidence of prior injury, hard or soft tissue abnormality, prior surgery, or disease, were used in this study. Tissues 10 cm from the joint line were removed, while the remaining structures were left intact. The femur, tibia, and fibula were potted in polymethylmethacrylate (Fricke Dental International Inc, Streamwood, Illinois).

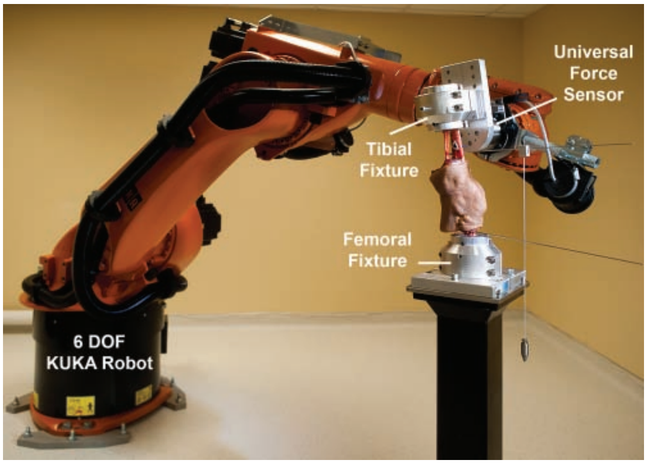

Figure 1. Robotic setup. The robotic system setup with knee mounted in a fixture attached to a universal force-torque sensor affixed to the end effector of a KUKA KR 60-3 6 degrees of freedom robot.

Robotic System

Each knee was secured into the robotic system in an inverted orientation. The tibia was clamped by use of a custom fixture mounted to a universal force-torque sensor (Delta F/T Transducer, ATI Industrial Automation, Apex, North Carolina) and installed on the end effector of a 6 degrees of freedom (DOF) robotic system (KR 60-3, KUKA Robotics, Augsburg, Germany) (Figure 1).

A coordinate measuring machine (MicroScribe MX GoMeasure3D, Amherst, Virginia) was used to select anatomic landmarks to define the coordinate systems for the femur, tibia, and knee.[20,42] These anatomic coordinate systems defined a clinically relevant direction of motion for control. Anatomic locations on the femur and tibia were selected with the knee in a neutral orientation. This neutral orientation was defined as the position of the knee while suspended from the end effector of the robotic system at full extension in free space. Eyelet pins were drilled perpendicular to the tibia and femur; a pointed-tip metallic weight (plumb-bob) hanging from the eyelet pin was used to assist in determining the neutral alignment of the knee during the intact state and as a reference during the selection of the neutral position for the sectioned and reconstructed knee states.

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Biomechanical Testing

The passive flexion path was determined from 0° (or full extension) to 90° by controlling and increasing the flexion angle by 1° increments. At each flexion angle, the remaining 5 DOF were controlled to minimize forces and torques (<5 N and <0.5 N·m, respectively) while an axial force of 10 N was applied until each DOF was satisfied; the corresponding passive path tibiofemoral position was recorded. During testing, a compressive force of 10 N was used to generate tibiofemoral contact and was applied along the long tibial axis to ensure proper contact between the femoral condyles and tibia. Movements were accomplished through position and force control in conjunction with force feedback from the universal force-torque sensor, which measured forces and torques in all 6 DOF. Internal validation determined a system force accuracy of 0.1 ± 0.6 N and point repeatability of 0.1 mm for root mean square error. The corresponding passive path positions were subsequently used as the starting points for laxity testing performed at the various knee flexion angles.

Knee laxity was assessed through several simulated clinical examinations with the use of previously reported tibiofemoral applied loads. Anterior knee laxity was tested by application of an 88-N anterior force to the tibia at 0°, 20°, 30°, 60°, and 90° of flexion.[2,15,44] Combined rotatory torques were applied to test rotational laxity with a simulated pivot-shift test of a coupled 10 N·m of valgus torque followed by 5 N·m of internal rotation torque applied to the tibia at 0°, 15°, 20°, and 30° of flexion.[2,13,15,25,26,36,44] Internal and external rotation torques of 5 N·m were applied at 0°, 20°, 30°, and 90° of flexion, while varus and valgus torques of 10 N·m were applied at 0° and 20° of flexion. The full series of tests were completed at each flexion angle before the next flexion angle was tested; the testing order of flexion angles was randomized between specimens to prevent any incremental testing bias that may affect states at the beginning or end of the testing sequence.

Surgical Technique

Grafts. Grafts were commercially prepared and selected to be of equal length and diameter. Fresh bovine extensor tendons (Innovative Medical Device Solutions, Logan, Utah) were used for all reconstructions to standardize graft size, condition, and properties and eliminate any specimen-to-specimen variability present in allografts; bovine extensor tendons have been previously used and reported to be biomechanically similar to human hamstring tendons.[1,2,12,33,40] Grafts were doubled over and measured to be 7 mm (DB) or 9 mm (SB) in diameter. Larger grafts were sharply trimmed parallel to the fiber orientation to ensure a consistent cross-sectional area. Both ends of the tendon grafts were whip-stitched with braided polyblend sutures (FiberLoop, Arthrex Inc, Naples, Florida) 25 mm from each end. A 50-N tensile force was used to precondition the graft 10 minutes before graft passage.[2] Grafts were kept moist to prevent desiccation.

Anatomic Single-Bundle ACL Reconstruction. All ACL reconstructions were performed by a single board-certified sports medicine orthopaedic surgeon (R.F.L.). Right and left knees were randomized between the anatomic SB and anatomic DB reconstruction groups. Reconstructions were performed with the knee fixed in the robot throughout all testing states to reduce possible testing error introduced from specimen removal.

The native ACL's tibial and femoral footprints were visually identified through a medial parapatellar arthrotomy to ensure accurate isolation of the individual bundles. Next, the ACL was sectioned under direct visualization. A drill guide was used to pass an eyelet guide pin through the center of the visualized tibial footprint of the ACL.[34,48] Pins were placed into both the tibia and the femur and assessed for proper anatomic location (Figure 2). The tibial tunnel was then reamed outside-in with a 9-mm diameter cannulated reamer (Arthrex Inc). Consistency with manufacturer and reamer type was emphasized during the surgical protocol to minimize aperture variability and tunnel dimensions.[17] A 9-mm closed-socket femoral tunnel, positioned between the AM and PL bundles, was reamed through the medial arthrotomy at 120° of knee flexion, which simulated the reaming position of an anteromedial arthroscopic portal. The graft was looped over an adjustable-length cortical button femoral fixation device (ACL TightRope RT, Arthrex Inc) and passed through the femoral tunnel socket. Initial tensioning of the fixation device was performed in accordance with the manufacturer's recommendations. The graft was then passed through the tibial tunnel and fixated with a 9×23-mm interference screw (Polyetheretherketone, PEEK, Interference Screw, Arthrex Inc) at 0° of knee flexion.[2,29] During distal graft fixation, a distal traction force of 20 N, which in previous studies has been reported to be sufficient to restore normal knee kinematics,[2,24] was applied using a graft tensioning device in line with the tunnel.

Anatomic Double-Bundle ACL Reconstruction. Anatomic DB ACL reconstructions followed previously published anatomic DB ACL reconstruction methods.[2,40] After direct visualization and removal of the native ACL bundles at the time of surgery, a drill guide was positioned over the footprints and guide pins were drilled for placement through the visualized centers of the AM and PL bundles to ensure an anatomic reconstruction (Figure 3).[34,48] Two guide pins were placed into both the tibia and the femur with maintenance of a 2-mm bone bridge between tunnels before both tunnels were reamed with a 7-mm-diameter cannulated reamer. Tibial tunnels were drilled outside-in, and closed-socket femoral tunnels were reamed at 120° of knee flexion through the medial parapatellar arthrotomy, similar to an anteromedial arthroscopic portal vantage point. As with the anatomic SB reconstruction, an adjustable-length cortical button femoral fixation device (ACL TightRope RT) was used. During distal graft fixation, a distal traction force of 20 N was applied using a graft tensioning device,[2,24] while two 7×23-mm interference screws (PEEK Interference Screw) were used for tibial fixation. The AM bundle was fixed at a 60° flexion angle and the PL bundle at 0° of flexion with the tibia in neutral rotation; selection of these fixation angles was based on previous work specifying the angles of fixation that prevent overconstraint of the individual bundles[2] and a commonly used clinical surgical protocol.[14]

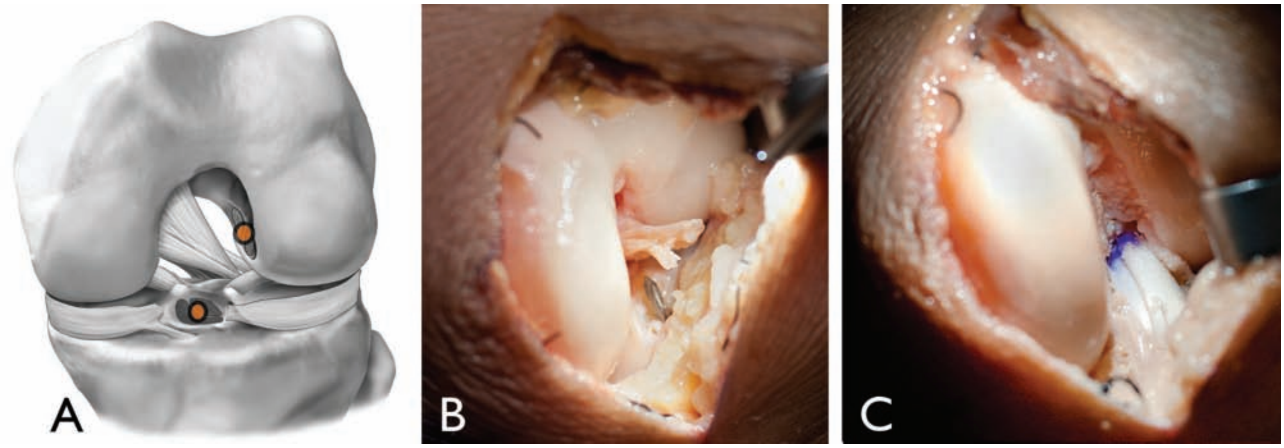

Figure 2. (A) Selection of the central anatomic tunnel location with reference to the anterior cruciate ligament (ACL) anteromedial and posterolateral bundle footprints for an anatomic single-bundle reconstruction. (B) Eyelet pin placement in the anatomic ACL footprint of the tibia. (C) A single, doubled-over, 9-mm bovine graft was passed between the anatomically drilled tunnels.

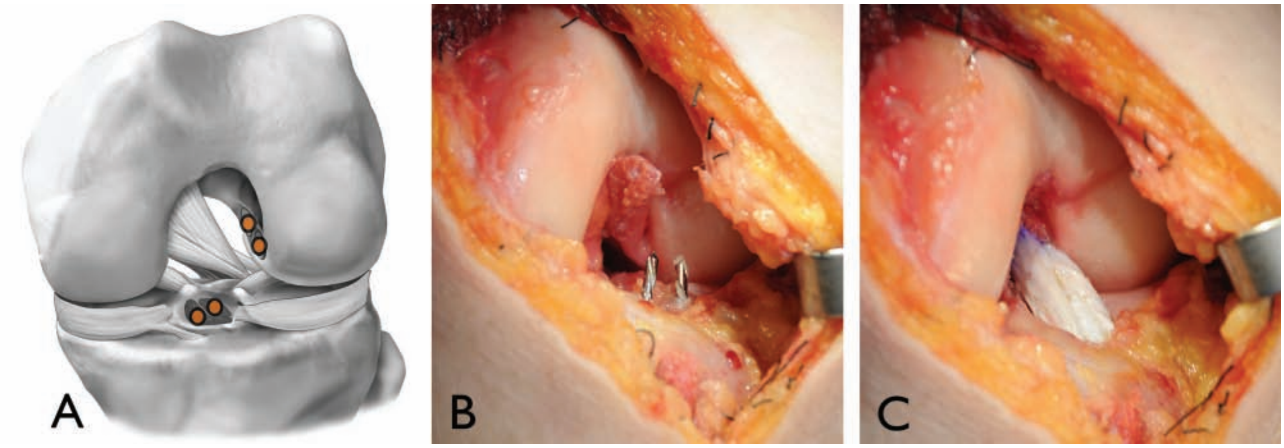

Figure 3. (A) Selection of the 2 anatomic tunnels, which were located centrally in the anterior cruciate ligament (ACL) anteromedial and posterolateral bundle footprints, for an anatomic double-bundle reconstruction. (B) Eyelet pin placement in the anatomic ACL footprints of the tibia. (C) Two doubled-over, 7-mm bovine grafts were passed between the anatomically drilled tunnels.

Statistical Analysis

Statistical analysis was performed using the Levene test for the equality of variance comparing relative displacement values for the sectioned and reconstructed states. A 1-sample Student *t* test was used to compare the sectioned, anatomic SB ACL reconstruction and the anatomic DB ACL reconstruction groups to their respective intact states. Two-sample independent *t* tests were used for comparison among the sectioned and reconstruction groups. Differences were considered statistically significant when $P < .05$.

The equivalence test was performed with a confidence interval (CI) method to determine whether anatomic SB and anatomic DB reconstructions could be considered clinically equivalent.[23] We constructed an overall 95% confidence level for the equivalence test by generating 90% CIs for the difference between reconstructions at each tested state. The calculated CI was compared with a minimal level of clinically important differences. If the CI fell completely below the threshold for the minimal level of clinically important difference, then the 2 reconstructions were considered equivalent. Anatomic SB and anatomic DB reconstructions were examined for equivalence for the anterior tibial load and simulated pivot-shift tests at all flexion angles. Thresholds specifying the minimal level of clinically significant difference were selected from the average calculated side-to-side variability in the intact state of each individual pair of tested cadavers, which we refer to as the *conservative threshold*, and from estimates obtained from the peer-reviewed literature for cutoff values for diagnosis,[5,8] which we refer to as the *clinical threshold*. For anterior tibial load, side-to-side variability between the matched pairs of knees across all flexion angles was calculated as an average of 1.0 mm (the conservative threshold); a clinical threshold was selected based upon previously published KT–1000 arthrometer data as

TABLE 1
Observed Translational and Rotational Differences Between Tested States[a]

	Anterior Tibial Load				Simulated Pivot Shift			
		Difference From Intact, mm				Difference From Intact, mm		
Flexion Angle	Translation at Intact State, mm (n = 18)	Sectioned (n = 18)	SBR (n = 9)	DBR (n = 9)	Translation at Intact State, mm (n = 18)	Sectioned (n = 18)	SBR (n = 9)	DBR (n = 9)
0°	3.8 ± 1.2	6.6 ± 2.4[i]	3.4 ± 1.4[i,s]	2.6 ± 1.4[i,s]	0.9 ± 0.7	3.1 ± 1.2[i]	2.1 ± 1.1[i]	1.8 ± 1.3[i,s]
15°	—	—	—	—	1.7 ± 1.0	3.6 ± 1.6[i]	2.4 ± 1.2[i]	1.9 ± 1.9[i,s]
20°	4.4 ± 1.3	7.9 ± 2.9[i]	3.9 ± 1.6[i,s]	2.6 ± 2.3[i,s]	1.9 ± 1.0	3.7 ± 1.8[i]	2.3 ± 1.2[i,s]	1.6 ± 2.0[i,s]
30°	4.6 ± 1.3	7.8 ± 3.2[i]	3.8 ± 1.8[i,s]	2.5 ± 2.2[i,s]	2.2 ± 1.2	3.2 ± 1.9[i]	1.7 ± 1.4[i,s]	1.2 ± 1.6[s]
60°	4.5 ± 1.5	5.8 ± 3.3[i]	3.8 ± 2.3[i]	2.3 ± 1.6[i,s]	—	—	—	—
90°	3.8 ± 1.7	4.4 ± 2.5[i]	2.4 ± 1.4[i,s]	1.4 ± 1.2[i,s]	—	—	—	—

	Internal Rotation				External Rotation			
		Difference From Intact, deg				Difference From Intact, deg		
Flexion Angle	Rotation at Intact State, deg (n = 18)	Sectioned (n = 18)	SBR (n = 9)	DBR (n = 9)	Rotation at Intact State, deg (n = 18)	Sectioned (n = 18)	SBR (n = 9)	DBR (n = 9)
0°	11.1 ± 2.9	2.4 ± 1.7[i]	2.1 ± 1.1[i]	1.4 ± 1.7[i]	11.8 ± 3.1	0.9 ± 1.3[i]	0.5 ± 0.9	1.1 ± 1.0[i]
20°	14.5 ± 4.9	2.0 ± 2.4[i]	2.1 ± 1.6[i,r]	0.2 ± 1.9[r]	15.5 ± 4.8	0.9 ± 2.1	–0.4 ± 1.6	1.3 ± 2.1
30°	16.6 ± 6.1	1.2 ± 3.2	1.8 ± 2.3[i,r]	–1.0 ± 2.9[r]	16.6 ± 5.7	1.3 ± 2.9	–0.7 ± 2.1	1.8 ± 3.0
90°	15.3 ± 6.6	0.9 ± 5.5	2.3 ± 4.5	–0.7 ± 4.5	18.6 ± 7.2	1.4 ± 4.9	–1.0 ± 4.2	1.6 ± 3.9

	Valgus Rotation				Varus Rotation			
		Difference From Intact, deg				Difference From Intact, deg		
Flexion Angle	Rotation at Intact State, deg (n = 18)	Sectioned (n = 18)	SBR (n = 9)	DBR (n = 9)	Rotation at Intact State, deg (n = 18)	Sectioned (n = 18)	SBR (n = 9)	DBR (n = 9)
0°	3.0 ± 0.7	1.2 ± 0.6[i]	0.7 ± 0.5[i,s]	0.5 ± 0.6[i,s]	2.8 ± 0.8	0.7 ± 0.4[i]	0.5 ± 0.4[i]	0.5 ± 0.4[i]
20°	3.9 ± 1.2	2.4 ± 1.4[i]	1.2 ± 0.7[i,s]	0.7 ± 0.8[i,s]	3.6 ± 1.1	0.5 ± 0.5[i]	0.1 ± 0.4	0.5 ± 0.5[i]

[a]Values are expressed as mean ± standard deviation. Measurements are reported relative to each knee's corresponding intact state. SBR, single-bundle reconstruction; DBR, double-bundle reconstruction.

Statistically significant difference from [i]intact state, from [s]sectioned state, and [r]between reconstructions ($P < .05$).

3 mm.[8,9] For the simulated pivot-shift threshold, an average of 1.3 mm was calculated as a conservative threshold, based on the intact specimens' side-to-side variability across all flexion angles. For the simulated pivot shift, a clinical threshold was chosen based on a reported cutoff value of 6 mm of anterior translation in the lateral compartment between positive and negative clinical pivot-shift examinations.[5] This value was scaled to the midpoint of the tibial plateau. We assumed a point equidistant between the most medial and lateral tibial plateau coordinates, and no corresponding translation at the medial compartment, due to the lack of observable differences between injured and noninjured states reported for the medial compartment.[5] A translation value of 3 mm for the midpoint of the proximal tibia was therefore derived as the clinical cutoff to separate clinically significant translations from native variations in the simulated pivot shift. Variance and t test calculations were performed in PASW (PASW v.18, IBM Corp, Chicago, Illinois), and equivalence calculations were performed in MATLAB (MATLAB 2008b, The MathWorks Inc, Natick, Massachusetts).

RESULTS

Anterior Tibial Load

No significant differences were found between the anatomic SB and anatomic DB reconstruction groups during an applied anterior tibial load. Anterior tibial translations in response to an 88-N anterior force are reported in Table 1. The differences between intact states and the sectioned, anatomic SB reconstructed, and anatomic DB reconstructed states are reported in Figure 4. After ACL sectioning, translation increased significantly at all flexion angles compared with the intact state.

The anatomic SB and anatomic DB groups were clinically equivalent for anterior translations at 0°, 20°, 30°, and 90° of flexion (Figure 5). Anatomic SB and anatomic DB reconstructed knees were significantly different from both the intact and sectioned states at all tested flexion angles, except for the anatomic SB group at 60° of flexion, which was not significantly different from the sectioned state. Relative to each knee's intact state, the anatomic SB reconstruction group demonstrated average increases in translation of greater

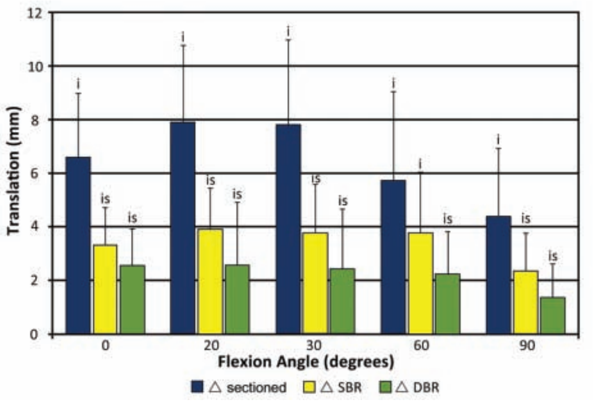

Figure 4. Average anterior tibial translation in response to an 88-N anterior force. Sectioned and reconstructed states are reported relative to each knee's corresponding intact state. DBR, double-bundle reconstruction; SBR, single-bundle reconstruction. Statistically significant difference from ^{i}intact and ^{s}sectioned state.

than 3 mm at all flexion angles except at 90° and showed an average increase of 3.5 mm of translation across all flexion angles. Similarly, for anatomic DB reconstruction group, although none of the tested flexion angles exceeded 3 mm of translation, the anatomic DB reconstruction group showed an average increase of 2.3 mm of anterior translation across all flexion angles compared with the intact knee state.

Simulated Pivot Shift

Anterior tibial translations in response to a combined 10-N·m valgus and 5-N·m internal rotation torque are reported in Table 1. No significant differences were observed when the anatomic SB reconstruction and anatomic DB reconstruction groups were compared with each other (Figure 6). All sectioned and reconstructed states demonstrated a significant increase in the anterior translation measured relative to the intact state except for the anatomic DB reconstruction at 30° of flexion, in which the displacement (1.2 mm from intact) was similar to the intact state. The anatomic SB reconstruction group was also significantly different from the sectioned state at 20° (2.3 mm vs 3.7 mm) and 30° (1.7 mm vs 3.2 mm) of flexion. The anatomic DB reconstruction group was significantly different from the sectioned state at all flexion angles. Compared with a clinical equivalence threshold, the anterior translations for the anatomic SB and anatomic DB reconstruction groups for a simulated pivot shift at 0°, 15°, 20°, and 30° of flexion were clinically equivalent (Figure 5).

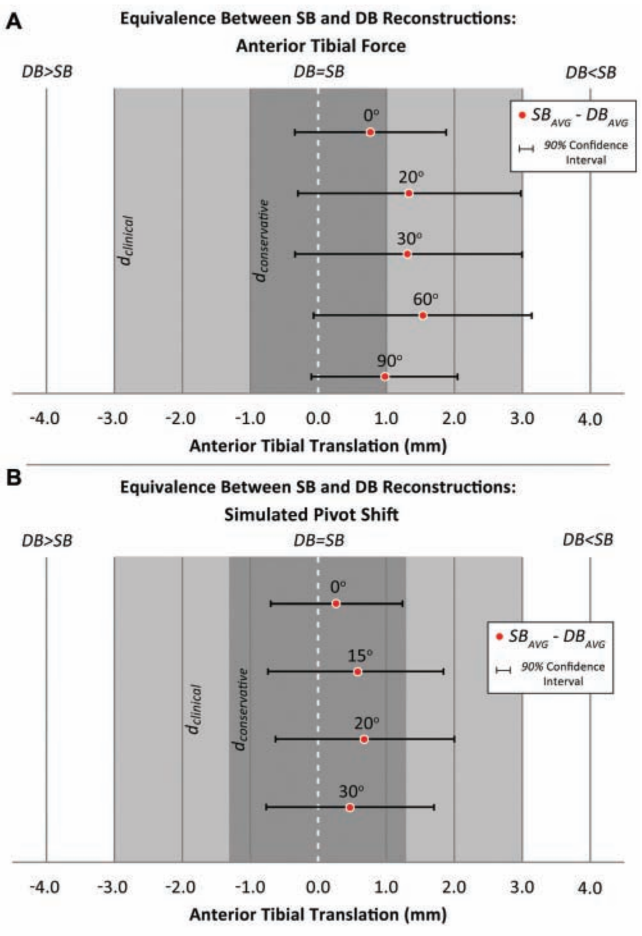

Figure 5. Comparison of (A) anterior tibial force and (B) simulated pivot shift translation differences between anatomic single-bundle (SB) and anatomic double-bundle (DB) anterior cruciate ligament (ACL) reconstructions with thresholds for minimal level of clinically important difference. Points represent differences between the anatomic SB and anatomic DB reconstruction group averages, while error bars represent the 90% confidence interval. Confidence intervals fully within the dark gray (side-to-side variability between matched pair's intact states) and light gray (clinical cutoff between intact and unstable knees) regions represent reconstructions considered clinically equivalent.

Internal/External and Varus/Valgus Rotation

Tibial rotations in response to 5-N·m internal/external torques and 10-N·m varus/valgus torques are reported in Table 1. No significant differences in rotation were observed between the anatomic SB and anatomic DB ACL reconstruction groups, with the exception of small (<3°), but statistically significant differences in internal rotation for anatomic SB versus anatomic DB at 20° (2.1° vs 0.2°, respectively, reported as difference from intact) and 30° (1.8° vs −1.0°, respectively) of knee flexion. Anatomic SB ACL reconstructions resulted in significantly increased internal rotation when compared with the intact state for 0° (2.1° difference from intact), 20° (2.1° difference from intact), and 30° (1.8° difference from intact) of flexion. Anatomic DB reconstruction was significant when compared with intact at 0° (1.4° difference from intact) of flexion.

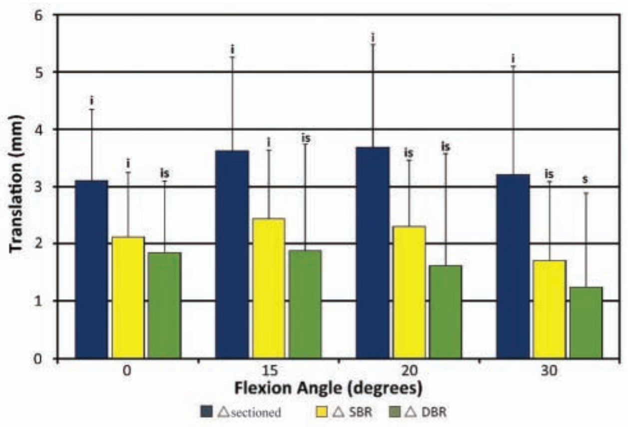

Figure 6. Average anterior tibial translation in response to a simulated pivot shift of 10-N·m valgus and 5-N·m internal rotation torques. Sectioned and reconstructed states are reported relative to each knee's corresponding intact state. Statistically significant difference from ^{i}intact and ^{s}sectioned state.

For valgus rotation, both anatomic SB and anatomic DB reconstruction groups had significantly reduced rotation when compared with the sectioned state at all flexion angles. However, there were small (0.5°-1.2°), yet significant increases from the intact state across flexion angles. For varus rotation, all reconstructions had small (<1°), yet significant increases from the intact state, with the exception of the anatomic SB at 20° of knee flexion, which was similar to intact (0.1° difference from intact).

DISCUSSION

We confirmed our hypothesis that comparable anterior-posterior translations could be achieved using either an anatomic SB or anatomic DB reconstruction technique. No significant differences in anterior translation were found between the anatomic SB and anatomic DB ACL reconstruction groups after a simulated pivot shift and anterior tibial forces were applied. Although significant differences were observed in internal rotation between the reconstruction groups, the small magnitude of these differences (<3°) between groups may not have clinical significance.

Differences between reconstructions were considered clinically equivalent for anterior translations during anterior loading and simulated pivot shift at all tested angles, with the exception of anterior tibial loading at 60° of flexion, according to an equivalence test that used previously published values for minimally significant clinical differences.[5,8] Both the anatomic SB and anatomic DB ACL reconstruction groups significantly decreased anterior translation in response to anterior tibial loads and the simulated pivot shift at most flexion angles compared with the sectioned state. During the simulated pivot shift, reconstructed groups were significantly different from the sectioned state at most tested angles, with the exception of the anatomic SB reconstruction at 0° and 15° of flexion, which confirmed that significant improvements in rotational laxity are possible after both anatomic reconstructions. Similarly, after anterior forces were applied, significant differences in anterior translations from the sectioned state for all tested conditions, except for the anatomic SB reconstruction at 60° of flexion, confirmed the improvements in laxity that occurred after both anatomic reconstructions.

Complementing the simulated pivot-shift test as an assessment of rotational laxity, applied rotational torques were used to test the resistance of the knee to various rotational torques. The only significant differences were observed between internal rotations of the anatomic SB and anatomic DB reconstruction groups at 20° and 30° of flexion, where the anatomic DB group more closely approximated the intact state. Despite the statistical significance of the rotational displacements, the small magnitude of these differences (<3° of internal rotation) between reconstruction groups suggests that these differences may not be of clinical significance for most patients. Rotations during the other loading conditions showed no significant differences. Statistical clinical equivalence between reconstructions, only small rotational differences, lack of significant anterior translation differences, and improvements in anterior translation compared with the sectioned state suggest that either an anatomic SB or anatomic DB ACL reconstruction technique would comparably produce significant improvements in anterior and rotational laxity.

Despite the similar behavior between the 2 anatomic reconstruction groups, neither technique was able to reproduce the intact state during an anterior tibial load. We noted that an average anterior tibial displacement of 3.5 mm remained for the anatomic SB reconstructions and 2.3 mm remained for the anatomic DB reconstructions across all tested flexion angles. We were unable to fully return to the intact kinematics, as determined by a significant difference between intact and reconstructed states, for simulated pivot shift, valgus rotation, and varus rotation. However, there was no significant difference for the anatomic DB reconstruction group with an applied simulated pivot shift at 30° of flexion and the anatomic SB reconstruction group with a varus rotation at 20° of flexion. The significant displacements remaining compared with the intact state after reconstruction suggest that despite the surgical intervention, improvements are still necessary for both anatomic SB and anatomic DB ACL reconstructions to more precisely achieve the intact state kinematics at time zero.

Other studies have attempted to quantify the kinematics of the intact, ACL-deficient, and ACL-reconstructed knee. Groups have used both robotic manipulation[30,31,44,46] and manual loading[2,27,40] to perform anterior drawer and simulated pivot-shift examinations in human cadaveric specimens. Variable amounts of anterior translation were reported between studies attributable to differences in specimen age, loads, and reconstruction techniques; however, similar trends of increasing and decreasing translation for the intact, ACL-deficient, and ACL-reconstructed states across flexion angles were observed.[30] In the present study, maximum anterior translation in response to an anterior tibial force was observed at 20° and 30°, consistent with previously reported data.[2,31,40,44,46] Despite lower translations observed during our pivot shift, our data agreed with prior studies that observed maximum anterior translation in response to a simulated pivot shift occurred near 20° or 30° of flexion.[30]

An in vitro study in 2002 by Yagi et al[44] used robotic manipulation to compare an SB reconstruction, which reconstructed only the AM bundle with an 11-o'clock/1-o'clock positioning, to an anatomic DB reconstruction. Although the authors reported trends similar to those found in the present study, namely, increasing and decreasing anterior translation as a function of flexion angle, Yagi et al found that the anatomic DB ACL reconstruction resulted in significantly less anterior translation than did the nonanatomic SB ACL reconstruction at full extension and 30° of flexion during anterior tibial loading and at both 15° and 30° of flexion for the simulated pivot shift. Differences in nonanatomic SB ACL reconstruction laxity reported by Yagi et al and the anatomic SB ACL reconstruction in the present study can be attributed to the reconstruction techniques used for the respective studies. The anatomic SB ACL reconstruction performed in the present study anatomically reconstructed both the anteromedial and posterolateral bundles and resulted in no clinically significant differences in knee laxity compared with the anatomic DB reconstruction. The nonanatomic SB ACL reconstruction technique reported by Yagi et al in 2002 attempted to reproduce the anteromedial bundle only, which demonstrates the importance of anatomic SB tunnel placement.

In a 2007 in vivo study by Yagi et al,[43] patients received either an anatomic DB reconstruction, SB reconstruction that reconstructed the AM bundle, or SB reconstruction that reconstructed the PL bundle and were evaluated for laxity 1 year postoperatively. Rotational laxity, as evaluated with an instrumented pivot-shift test, was reported to be improved after anatomic DB reconstruction relative to either SB reconstruction technique. This differs from the findings of the present study, where no significant differences were observed between the anatomic SB and anatomic DB ACL reconstruction techniques in response to the simulated pivot shift, anterior tibial loads, external torque, and varus/valgus torques. However, our findings of significant improvements in internal rotation for the anatomic DB reconstruction observed at 20° and 30° of flexion similarly suggest rotational laxity improvements compared with anatomic SB reconstructions. The current study suggests that anatomic positioning of the SB ACL reconstruction may improve rotational laxity to levels comparable with anatomic DB ACL reconstruction techniques, as can be seen in comparable simulated pivot-shift results, but that some residual differences may remain in the rotational laxity between the anatomic SB and anatomic DB ACL reconstructions, as demonstrated in statistical differences during internal rotation testing.

Compared with previous investigators who evaluated anatomic SB and anatomic DB ACL reconstruction procedures, Seon et al[36] used an anterior tibial load and combined valgus and internal tibial rotation torques to observe that DB reconstructions could better restore the normal anterior-posterior and medial-lateral laxities than could SB reconstructions. These authors observed that DB reconstruction restored the anterior tibial translations to the intact knee kinematics under anterior tibial load and combined torques; however, the DB reconstruction overconstrained internal tibial rotation during applied combined torques at both 0° and 30° flexion angles. Our results demonstrated that anatomic DB reconstructions improved anterior translations at all flexion angles when compared with the sectioned state for both anterior tibial load and simulated pivot shift. However, our anatomic DB reconstruction remained significantly different from the intact state at all flexion angles with the exception of 30° of knee flexion during simulated pivot shift. Although we found minor overconstraints in internal rotation at 30° and 90° of flexion, these differences were not significant. When comparing reconstruction with the sectioned state, Seon et al[36] concluded that their SB ACL reconstruction improved the anterior tibial translations to a clinically satisfactory level but could not restore them to the intact state. Similarly, our results for anatomic SB ACL reconstruction showed improvements from the ACL-deficient state of the knee, but we were unable to achieve intact state kinematics during anterior tibial loading and simulated pivot shift. The similarities in surgical methods and differences in reported anterior translational laxity indicate that anatomic SB and anatomic DB reconstructions need to be further investigated.

There were some limitations of the present study. First, the average age of our cadaver population (46.7 years) may be higher than that of the patient population of ACL surgeries.[22] However, the average age of our cadaver population was younger than that reported in many comparable biomechanical studies.[40,44,46] Second, in contrast to the highly dynamic pivot-shift test used clinically, the simulated pivot-shift tests are performed at static flexion angles and do not precisely mimic the dynamic in vivo pivot-shift test. Third, our biomechanical testing of the knee lacks implementation of muscle loading. Even without muscle loading, this testing method represents an effective means of isolating the effects of surgical technique in this controlled laboratory study. And finally, this study used a cadaver model with robotic manipulation simulating clinical examinations at time zero, which does not incorporate biological healing or effects of rehabilitation. Appropriate caution should be exercised when translating these in vitro results to in vivo clinical conditions.

Selection of an optimal ACL surgical technique remains a debate that must balance financial and technical challenges with the proposed benefits of each technique. Quantitative descriptions of ACL anatomy have set the stage for improvements in surgical technique that aim to more accurately achieve the native positioning and function of the ACL. Recent anatomy studies of the ACL[48] have resulted in anatomic SB ACL reconstruction tunnels placed centrally between the AM and PL bundle attachment sites, with the aim of equally restoring both bundle functions rather than primarily restoring the function of a single bundle. Use of a more expensive and technically challenging DB ACL reconstruction technique motivates researchers to explore whether significantly better outcomes can be achieved with the technique compared with anatomic SB reconstructions, either at time zero or with long-term clinical outcomes.

CONCLUSION

The present study found no significant differences in anterior tibial translation between the 2 anatomic ACL reconstruction groups after both a simulated pivot shift and anterior tibial forces were applied. Differences in rotational laxity were statistically significant yet minimal per clinical standards. Future studies should examine this significant time zero rotational difference to determine whether there is a long-term clinical effect.

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