ACL Graft Position Affects in Situ Graft Force Following ACL Reconstruction

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Background: The purpose of our study was to evaluate the relationship between graft placement and in situ graft force after anterior cruciate ligament (ACL) reconstruction.

Methods: Magnetic resonance imaging (MRI) was obtained for twelve human cadaveric knees. The knees, in intact and deficient-ACL states, were subjected to external loading conditions as follows: an anterior tibial load of 89 N at 0°, 15°, 30°, 45°, 60°, and 90° of flexion and a combined rotatory (simulated pivot-shift) load of 5 Nm of internal tibial torque and 7 Nm of valgus torque at 0°, 15°, and 30° of flexion. Three ACL reconstructions were performed in a randomized order: from the center of the tibial insertion site to the center of the femoral insertion site (Mid), the center of the tibial insertion site to a more vertical femoral position (S1), and the center of the tibial insertion site to an even more vertical femoral position (S2). The reconstructions were tested following the same protocol used for the intact state, and graft in situ force was calculated for the two loadings at each flexion angle. MRI was used to measure the graft inclination angle after each ACL reconstruction.

Results: The mean inclination angle (and standard deviation) was 51.7° ± 5.0° for the native ACL, 51.6° ± 4.1° for the Mid reconstruction ($p = 0.85$), 58.7° ± 5.4° for S1 ($p < 0.001$), and 64.7° ± 6.5° for S2 ($p < 0.001$). At 0°, 15°, and 30° of knee flexion, the Mid reconstruction showed in situ graft force that was closer to that of the native ACL during both anterior tibial loading and simulated pivot-shift loading than was the case for S1 and S2 reconstructions. At greater flexion angles, S1 and S2 had in situ graft force that was closer to that of the native ACL than was the case for the Mid reconstruction.

Conclusions: Anatomic ACL reconstruction exposes grafts to higher loads at lower angles of knee flexion.

Clinical Relevance: Rehabilitation and return to sports progression may need to be modified to protect an anatomically placed graft after ACL reconstruction.

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Despite improved knee function compared with traditional transtibial surgery[1,2], the rate of graft failure following anatomic anterior cruciate ligament (ACL) reconstruction has been reported to be as high as 13%[3], while the failure rate for transtibial ACL reconstruction has been reported to be approximately 7%[4,5]. A recent study[6] showed a cumulative revision rate at four years of 5.2% for the anteromedial (AM) portal technique compared with 3.2% for the transtibial approach. The majority of graft failures following anatomic reconstruction occur six to nine months after surgery[3], when it is common for patients to return to full sports participation, but when the graft is not fully mature[7].

Of seventy-four studies that were reviewed relating to anatomic reconstruction, van Eck et al. found that only a few

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TABLE I Anterior Tibial Translation (mm) During Anterior Loading by Knee Flexion Angle*

	0°	15°	30°	45°	60°	90°
Intact native ACL	4.8 ± 1.2	6.7 ± 0.10	7.2 ± 1.1	6.3 ± 1.1	5.3 ± 0.9	4.8 ± 1.0
ACL-deficient	10.3 ± 2.3†	15.8 ± 2.8†	16.0 ± 3.2†	13.3 ± 3.7†	10.8 ± 3.1†	6.8 ± 6.4
Mid reconstruction	3.8 ± 1.4‡	7.2 ± 1.3	7.1 ± 5.2	8.2 ± 1.2†	7.3 ± 1.1†	7.0 ± 1.5
S1 reconstruction	6.2 ± 1.3†	8.9 ± 2.1†	8.8 ± 2.0‡	7.6 ± 2.3	6.3 ± 2.3	5.0 ± 2.1
S2 reconstruction	7.6 ± 2.4†	10.8 ± 2.3†	10.3 ± 2.3†	8.1 ± 2.2‡	6.3 ± 2.1	3.5 ± 3.6

*The values are presented as the mean and the standard deviation. †Significantly different from intact native ACL at $p < 0.001$. ‡Significantly different from intact native ACL at $p < 0.01$.

reported objective methods that documented an anatomic position of the graft[8]. Illingworth et al. determined that the normal ACL is inclined from 43° to 57° degrees in sagittal-view magnetic resonance (MR) reconstructions, a view which serves to determine if the graft is positioned anatomically[9].

Because anatomic placement may be associated with a higher rate of graft failure, we sought to determine if a more anatomic positioning of the graft (as indicated by a lower inclination angle) caused increased in situ force. Therefore, the purpose of this study was to determine the in situ force on the ACL graft and associated knee anterior translations after three different ACL reconstructions compared with that of the intact ACL. It was hypothesized that the in situ force in the graft would decrease with increasing graft inclination angle. It was also hypothesized that differences in graft in situ force may not be related to the anterior laxity of the knee. If increased in situ force is observed in an anatomically placed graft, then more conservative postoperative rehabilitation and slower return to sports progression may be required.

Materials and Methods

Prior approval was obtained for this study from the Committee for Oversight of Research and Clinical Training Involving Decedents. Twelve cadaveric knees were used (three from female donors and nine from nine male donors; mean age at death, 60.9 years [range, thirty-eight to seventy-nine years]). Prior to testing, magnetic resonance imaging (MRI) and computed tomography (CT) of the knees was performed to check for any abnormalities and to measure the native ACL inclination angle, according to the methods described by Illingworth et al.[9]. The knees were frozen at −20°C and thawed twenty-four hours prior to testing. The soft tissues beyond 15 cm proximal and distal to the knee joint were removed. The femur and the tibia were potted in cylindrical molds of an epoxy compound (Bondo; 3M) and mounted to aluminum cylinders. Specimens were kept moist with physiologic saline solution.

Robotic Testing System with Universal Force-Moment Sensor (UFS)

The joint was defined as being at full extension (0° of flexion) when a small extension moment, approximately 2 N at 15 cm from the joint line, was applied to the knee. Other kinematic degrees of freedom (anterior-posterior position, internal-external rotation, and varus-valgus rotation) were defined as zero in this configuration.

The femoral cylinder was attached to a fixed base, and the tibial cylinder was attached to the arm of the robotic testing system (Fig. 1). The testing system included a robot (CASPAR Stäubli RX90, Orto Maquet) with a UFS (Model 4015; JR3). The repeatability of motion was ± 0.02 mm at each joint for the robot, and the load cell had an accuracy ± 0.2 N and ± 0.1 Nm, according to the manufacturers. The system could control the displacement and the forces and moments applied to the knee in all six degrees of freedom[10]. Control and data acquisition were accomplished using a MATLAB program (MathWorks). Similar to that of a previous study[11], the origin of the tibial coordinate system was centered in the tibial plateau, with the proximal-distal axis parallel to the long axis of the tibia, with the medial-lateral axis connecting the medial and lateral tibial plateau prominences, and with the anterior-posterior axis being mutually perpendicular to these other two axes.

The six degrees-of-freedom path of passive flexion-extension of the intact knee was determined in 0.5° increments, from full extension to 90° of knee flexion[11], by minimizing forces and moments in the other degrees of freedom. The knees were tested intact, after ACL resection, and after each ACL reconstruction. To determine the anterior knee laxity over a range of flexion values, an anterior tibial load of 89 N (simulating a KT-1000 test)[12,13] was applied to the specimens at 0°, 15°, 30°, 45°, 60°, and 90° degrees of knee flexion, as described by Oster et al.[14]. For the anterior knee laxity measurements, the flexion angle was kept fixed while the other degrees of freedom were allowed to vary so as to achieve a force of 89 N in the anterior direction and

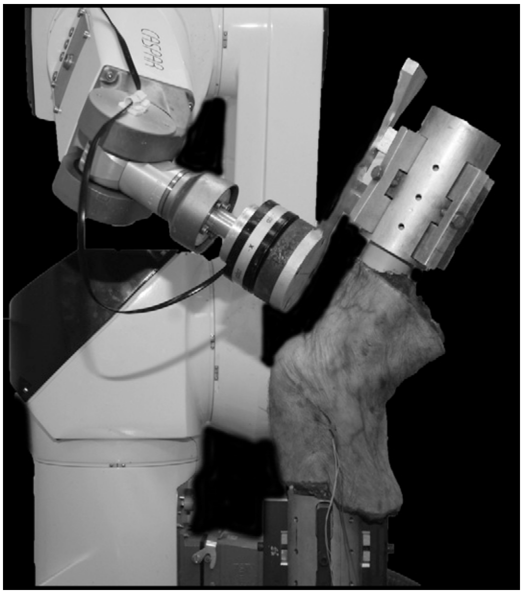

Fig. 1
The robotic system used in the study. The specimen was placed in an inverted position.

TABLE II Anterior Tibial Translation (mm) During Simulated Pivot-Shift Loading by Knee Flexion Angle*

	0°	15°	30°
Intact native ACL	2.4 ± 1.5	4.5 ± 2.9	5.7 ± 3.4
ACL-deficient	4.5 ± 2.8†	7.1 ± 3.9†	6.8 ± 4.0‡
Mid reconstruction	2.3 ± 1.5	4.5 ± 2.7	5.0 ± 2.9
S1 reconstruction	3.5 ± 2.2‡	6.3 ± 3.5§	6.3 ± 3.6
S2 reconstruction	3.9 ± 2.0†	6.8 ± 3.5†	6.9 ± 3.6†

*The values are presented as the mean and the standard deviation. †Significantly different from intact native ACL at $p < 0.01$. ‡Significantly different from intact native ACL at $p < 0.05$. §Significantly different from intact native ACL at $p < 0.001$.

minimize the other forces and moments. This mimicked an anterior drawer test at a fixed knee flexion angle, where an anterior load is applied and other degrees of freedom are unconstrained. No compressive loading was applied to the joint. Loads were applied at a slow rate, approximately 5 mm/min, a situation that can be considered quasi-static loading.

To assess rotational knee behavior, a simulated pivot-shift test was performed, whereby combined 5-Nm internal tibial and 7-Nm valgus torques were applied at fixed flexion angles of 0°, 15°, and 30°, with the other kinematic degrees of freedom again being unconstrained[15-17].

ACL Reconstructions

Under arthroscopic visualization, using the three-portal technique[18], the ACL was resected and its remnants preserved. Three femoral tunnels were created in the lateral wall of the intercondylar notch, using an outside-in drilling technique. A 7-mm drill bit was chosen to allow the drilling of the three tunnels with a 2-mm wall between each (as measured with an arthroscopic ruler prior to creating each subsequent tunnel). The first tunnel (Mid) was positioned in the center of the ACL insertion site, which was identified by the tissue remnants and the intercondylar and bifurcate ridges. The second tunnel (S1) was more vertical/superior and was drilled toward the "high AM" position. The third tunnel (S2) was even more vertical/superior. Note that the S1 and S2 femoral tunnels were not intentionally drilled to simulate the isometric position. Rather, those femoral tunnels were positioned so as to incrementally increase the graft inclination angle as measured on sagittal MRI. A single 7-mm tunnel was drilled in the center of the ACL tibial insertion site (Mid) (Fig. 2). After the tunnels were created, each knee was tested in the ACL-deficient state.

The three ACL reconstructions were performed in random order. For each knee, all three reconstructions used the same hamstring graft (Fig. 3). We secured the graft with a post screw and spiked washer on both the tibial and femoral sides. The graft was fixed at 15° degrees of knee flexion (measured with a manual goniometer), according to the senior author's (F.H.F.'s) protocol for single-bundle ACL reconstruction. This involved 40 N of tension, applied with use of a manual tensiometer (Smith & Nephew). This tension was based on previous studies of ACL single-bundle reconstruction[19,20]. After each reconstruction, the knees were biomechanically tested using the robotic system and underwent MRI with the graft in place to measure graft inclination[9]. A final CT scan was obtained to illustrate the position of the femoral tunnels in a three-dimensional (3-D) image. Mimics software (Materialise) was used to create 3-D

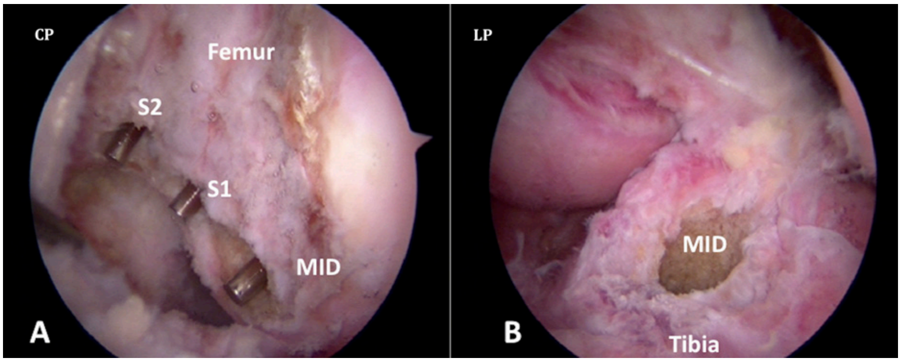

Fig. 2

Figs. 2-A and 2-B The femoral and tibial tunnels. **Fig. 2-A** The Mid, S1, and S2 femoral tunnels, with a 2-mm distance between them. **Fig. 2-B** The tibial tunnel in the center of the tibial footprint (Mid position). CP = central portal, and LP = lateral portal.

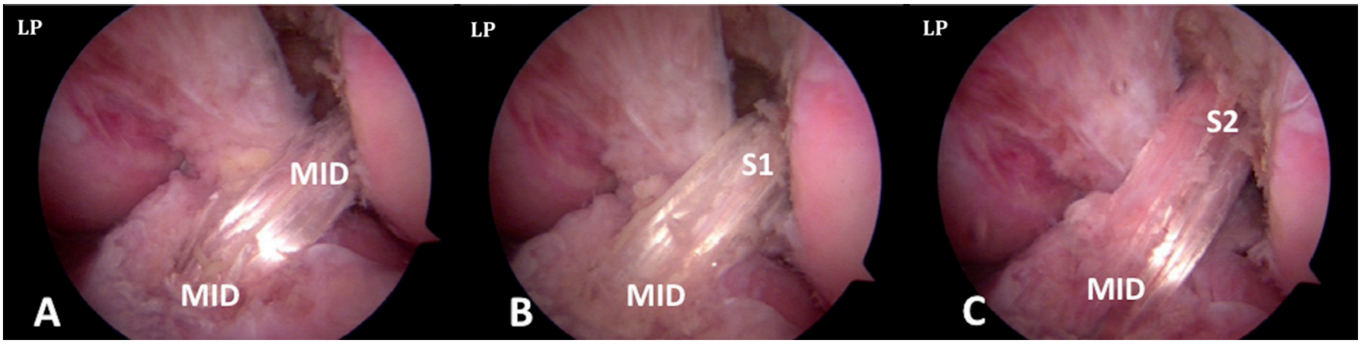

Fig. 3

Figs. 3-A, 3-B, and 3-C The three ACL reconstructions with increasing vertical graft positioning. **Fig. 3-A** The center of the tibial insertion site (Mid) to the center of the femoral insertion side (Mid). **Fig 3-B** Tibial Mid to femoral S1. **Fig. 3-C** Tibial Mid to femoral S2. LP = lateral portal.

TABLE III In Situ Force (N) in the Native ACL and Graft During Anterior Tibial Loading by Knee Flexion Angle*

	0°	15°	30°	45°	60°	90°
Intact native ACL	77.9 ± 11.1	82.8 ± 8.7	75.3 ± 9.6	65.2 ± 13.5	54.8 ± 14.4	53.3 ± 13.4
Mid reconstruction	78.6 ± 6.9	78.3 ± 10.1†	63.7 ± 15.0‡	44.1 ± 18.6§	31.2 ± 19.9§	25.9 ± 14.6§
S1 reconstruction	59.6 ± 13.3§	71.3 ± 14.1§	62.1 ± 17.2§	49.3 ± 19.5§	39.5 ± 19.9§	39.9 ± 19.5‡
S2 reconstruction	47.1 ± 16.8§	61.7 ± 18.9‡	56.8 ± 21.4‡	48.9 ± 19.8‡	41.0 ± 23.4‡	48.9 ± 20.5

*The values are given as the mean and the standard deviation. †Significantly different from intact native ACL at $p < 0.05$. ‡Significantly different from intact native ACL at $p < 0.01$. §Significantly different from intact native ACL at $p < 0.001$.

reconstructions to verify the tunnel position and the increasingly vertical location on the lateral wall of the intercondylar notch (Fig. 4).

In Situ Force

After each ACL reconstruction, external loads were applied to the reconstructed knee, and the motion was measured. After removal of the graft, the motion was replayed to determine the in situ force experienced by the graft. By the principle of superposition, the change in the force before versus after graft removal, with the knee in the same position, represents the in situ force in the graft[11].

Data Analysis

Data analysis began with the calculation of descriptive statistics, including frequency counts and percentages for frequency variables, and measures of central tendency (means and medians) and dispersion (standard deviation and interquartile range) for continuous variables. Separate general linear models (GLMs) were created with a single within-subjects factor (with five levels: intact ACL, transected ACL, Mid reconstruction, S1 reconstruction, and S2 reconstruction) to detect differences in the in situ force and inclination angle between the native ACL, transected ACL, and each femoral tunnel placement. To determine if the in situ force for each reconstruction was significantly different from that of the intact ACL, planned pairwise contrasts were performed using paired t tests to compare the amount of force. The level of significance for all statistical tests was set at $p < 0.05$.

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Results

The mean (and standard deviation) of the inclination angle for the native ACL was 51.7° ± 5.0°. The graft inclination angle increased significantly in comparison with the native ACL for the S1 (58.7° ± 5.4°; $p < 0.001$) and S2 (64.7° ± 6.5°; $p < 0.001$) reconstructions. However, there was no significant difference in inclination angle between the native ACL and Mid reconstruction (51.6° ± 4.1°; $p = 0.85$).

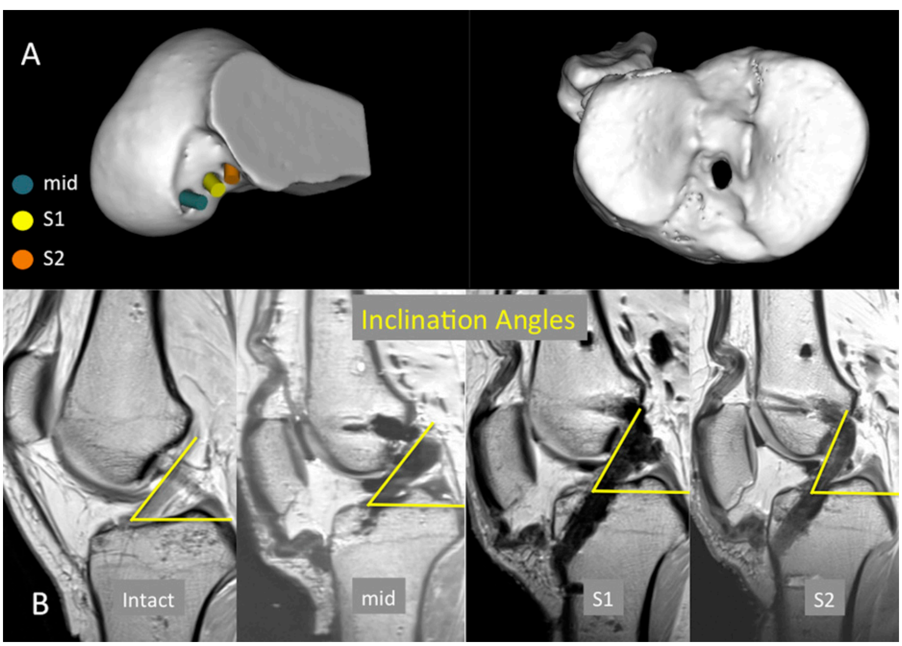

Fig. 4

Figs. 4-A and 4-B Femoral tunnel placement. **Fig 4-A** 3-D CT scan confirming the femoral tunnel in the Mid (anatomic), S1, and S2 positions, which were increasingly vertical. The tibial tunnel (right panel) was in the center of the anatomic insertion site. **Fig. 4-B** The inclination angle of the native ACL and of each of the reconstructions in a typical specimen, attesting to increasingly vertical positioning of the graft.

TABLE IV In Situ Force (N) in the Native ACL and Graft During Simulated Pivot Shift by Knee Flexion Angle*

	0°	15°	30°
Intact native ACL	37.1 ± 7.3	48.5 ± 13.4	44.5 ± 23.3
Mid reconstruction	43.4 ± 8.4†	47.0 ± 12.2	36.4 ± 17.1
S1 reconstruction	27.4 ± 12.5	28.5 ± 19.1‡	20.8 ± 11.4‡
S2 reconstruction	19.8 ± 7.9§	18.9 ± 10.0§	14.8 ± 7.3§

*The values are presented as the mean and the standard deviation. †Significantly different from intact native ACL at $p < 0.05$. ‡Significantly different from intact native ACL at $p < 0.01$. §Significantly different from intact native ACL at $p < 0.001$.

The anterior tibial translation during anterior tibial loading and simulated pivot-shift loading are given in Table I and Table II, respectively.

The in situ force in the native ACL and graft for each reconstruction at 0°, 15°, 30°, 45°, 60°, and 90° of flexion during anterior tibial loading are given in Table III and for the simulated pivot-shift loading at 0°, 15°, and 30° of flexion in Table IV.

Discussion

We found that, for knee flexion of ≤30°, lower positioning of the graft, represented by the Mid reconstruction, was associated with in situ graft force that was not significantly different from that in the native ACL, specifically under anterior tibial loading at 0° of knee flexion, and at 15° and 30° of knee flexion during the simulated pivot shift. In addition, the Mid reconstruction better restored the intact ACL knee anterior laxity at lower flexion angles, while the vertical reconstructions better restored the laxity at higher flexion angles.

Changing the graft location on the femur from the anatomic (Mid) position to the more vertical (S1) and even more vertical (S2) positions led to an increase in the graft inclination angle and a decrease in graft in situ forces during the simulated pivot-shift test. The Mid position better restored the knee laxity under simulated pivot-shift loading.

These results indicate that, compared with nonanatomically placed grafts (S1 and S2), an anatomic graft (Mid) may be at higher risk for failure when the knee is positioned at ≤30° of flexion, which includes the range where most ACL injuries occur[21].

At ≥45° of knee flexion, higher tunnel position led to increasingly higher in situ graft force, closer to the loads in the native ACL. Kato et al.[22] found that the vertical position of the femoral tunnel in the so-called "PL (posterolateral) to high AM" graft position produced greater in situ force compared with a lower graft (mid-tibial insertion to mid-femoral insertion) reconstruction at >30° of knee flexion. Sakane et al. found that the AM bundle has higher in situ force at larger angles of knee flexion, while the PL bundle has higher in situ force at lower angles of knee flexion[11]. A possible explanation for the present findings is that the S1 and S2 femoral tunnels were more vertical and more representative of the AM bundle position. However, despite the higher in situ force experienced by the more vertical grafts (the S1 and S2 reconstructions) during anterior tibial loading at ≥45° of flexion, the graft may not be at correspondingly greater risk for injury, because the ACL is rarely injured with the knee in this position[21]. We found that knee anterior laxity was related to the graft in situ force, with a greater force being found in knees with lower laxity.

Sim et al. studied native ACL and ACL graft in situ force and kinematics for ACL reconstructions performed by drilling the femoral tunnel using the AM portal or transtibial technique or a two-incision outside-in approach[20]. Anatomic ACL reconstruction was achieved only when the femoral tunnel was created using the AM portal or outside-in approaches. They found no differences between the intact ACL and the ACL graft in situ force for any of the reconstruction methods during anterior tibial loading. Those results differ from those observed in the current study; no significant differences were found between the native ACL and the anatomically placed ACL graft in situ force under anterior tibial loading at 0° of knee flexion, but at the remaining angles of knee flexion, we found significant differences between the native ACL versus the anatomic (Mid) reconstruction and native ACL versus the nonanatomic (S1 and S2) reconstructions. Under a simulated pivot-shift load, Sim et al. found significant differences between the native ACL and only the transtibial approach at 0° of knee flexion and between the native ACL and all of the approaches—transtibial, outside-in, and AM portal—at 30° of flexion. Their study found that the graft in situ force was always lower than the native ACL in situ force, but significantly so only in the cases mentioned above. Similarly, our study found that, for simulated pivot-shift loading at 0° of knee flexion, the S2 reconstruction had a lower in situ force than the intact ACL and that, at 30° of knee flexion, the force for all reconstructions was lower than that for the intact ACL, but significantly so only for S1 and S2. On the basis of the limited data that can be compared between the two studies (i.e., at 0° to 30° of knee flexion), in general, the simulated pivot-shift loads produced higher in situ graft force at low knee flexion angles (≤15°) when the tunnels were placed in an anatomic position compared with nonanatomic placement.

ACL reconstruction has transitioned toward methods of "anatomic" reconstruction over the last decade. However, no changes have been made to the rehabilitation and return-to-sports guidelines, to account for the increased in situ force that has been observed with anatomic placement of the graft. van

Eck et al. reported failure rates of up to 13% for anatomic ACL reconstructions, either single or double bundle, using allografts in patients under twenty-five years old[3]. The peak time for graft failure was between six and nine months postoperatively, which is the most commonly recommended time period for return to sports. Although objective parameters for return to sports (e.g., muscle strength and neuromuscular control) may have been met during this time frame, complete graft healing and maturation may take longer to occur[23,24]. Similarly, the Danish Knee Ligament Reconstruction Register showed a cumulative revision rate at four years of 5.2% when an AM portal approach was used to drill the femoral tunnel—an approach that is expected to provide a more anatomic placement and, therefore, a lower inclination angle—compared with a 3.2% revision rate for the transtibial technique[6]. The higher force experienced by the more anatomically placed grafts could be a possible explanation for these findings.

We acknowledge that the nonanatomic ACL reconstructions performed in this study (S1 and S2) do not correspond to traditional transtibial reconstruction, because the tibial tunnel was positioned in the center of the tibial footprint rather than in the PL insertion site, as is typically done during transtibial reconstruction. However, the inclination angles that resulted from the S1 and S2 reconstructions were similar to what is frequently seen in nonanatomic reconstructions in a clinical situation. Illingworth et al.[9] showed that the average sagittal inclination angle for nonanatomic reconstructions was 62.3° ± 7.8°, and specifically for transtibial reconstructions, it was 63.5° ± 7.2°. In the current study, the inclination angle for the S1 and S2 reconstructions was 58.7° ± 5.4° and 64.7° ± 6.5°, respectively.

Considerable variability was observed in the current study data. Relatively large standard deviations can occur in the measurements of in situ tissue force[20] in both the intact ACL and reconstructed specimens at certain flexion angles, but we found no specific pattern. It is assumed that the variation was due to natural variations in knee osseous and soft-tissue morphology rather than to any methodological variations.

Our study considered two distinct loading conditions: anterior tibial loading, replicating a commonly used clinical test; and simulated pivot-shift test, so as to attempt to replicate the most common mechanism of ACL tear. The study had the limitation of the robotic loads being applied quasi-statically to the knee, and moreover, without muscle forces. While reasonably simulating KT-1000 clinical testing, the study's anterior tibial loading regime may not be representative of dynamic physiologic loads. In addition, there was variability in the passive motion path of each specimen and, therefore, variation in force and anterior translation results. Another limitation was that the same hamstring autograft was used for the three reconstructions in each cadaveric specimen, which may have affected graft behavior. Although the effects of the repeated graft use are unknown, the loads placed on the graft were relatively low. To minimize possible bias in the results, the order in which each reconstruction was made was randomized.

In conclusion, our study demonstrated that the anatomic (Mid) ACL reconstruction resulted in a lower graft inclination angle than that of nonanatomic ACL reconstruction; the Mid inclination angle was closer to the native ACL inclination angle. The anatomic (Mid) ACL reconstruction led to graft force and knee anterior laxity closer to those of the native knee for both anterior tibial load and simulated pivot-shift load at ≤30° of knee flexion. Finally, at ≤30° of knee flexion, the in situ ACL graft force decreased as the inclination angle increased, which we attribute to locating the femoral tunnel at a higher position on the lateral wall of the intercondylar notch. ■

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