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The Effect of an ACL Reconstruction in Controlling Rotational Knee Stability in Knees with Intact and Physiologic Laxity of Secondary Restraints as Defined by Tibiofemoral Compartment Translations and Graft Forces

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Background: The effect of an anterior cruciate ligament (ACL) reconstruction on restoring normal knee kinematics in unstable knees with physiologic laxity of secondary ligamentous restraints remains unknown. The purpose of this study was to determine the stabilizing function of an ACL reconstruction and the resulting ACL graft forces in knees with severely abnormal anterior subluxation due to associated laxity of secondary restraints.

Methods: A 6-degree-of-freedom robotic simulator was used to test 21 cadaveric knees studied as a whole and in subgroups of lax secondary restraints (Lax-SR) and intact secondary restraints (Intact-SR), based on abnormal translations and tibial rotations. Native, ACL-sectioned, and ACL-reconstructed conditions were tested. An instrumented bone-patellar tendon-bone (BPTB) graft measured ACL graft forces. The loading profile involved the Lachman test (25° of flexion and 100-N anterior load), anterior tibial loading (100-N anterior load across 10° to 90° of flexion), internal rotation (25° of flexion and 5-Nm torque), and 2 pivot-shift simulations (100-N anterior load, 7-Nm valgus, and either 5 Nm of internal rotation [Pivot Shift 1] or 1 Nm of internal rotation [Pivot Shift 2]). Equivalence between conditions was defined as being within 2 mm for compartment translation and within 2° for internal tibial rotation, with $p < 0.05$.

Results: ACL sectioning increased center translation in the Lachman test by a mean of 10.9 mm (95% confidence interval [CI], 9.3 to 12.5 mm; $p = 0.99$), which was equivalent to native values after ACL reconstruction in all knees (mean difference, 0.0 mm [95% CI, -0.4 to 0.4 mm]; $p = 0.0013$), and in subgroups of Lax-SR (mean difference, 0.2 mm [95% CI, -0.5 to 0.8 mm]; $p = 0.03$) and Intact-SR (mean difference, -0.2 mm [95% CI, -0.8 to 0.4 mm]; $p = 0.002$). ACL sectioning in the pivot-shift (5-Nm) test increased lateral compartment translation to non-native-equivalent levels, which were restored to native-equivalent values after ACL reconstruction in all knees (mean difference, 0.9 mm [95% CI, 0.4 to 1.4 mm]; $p = 0.055$), in the Intact-SR subgroup (mean difference, 1.1 mm [95% CI, 0.5 to 1.8 mm]; $p = 0.03$), and to nearly native-equivalence in the Lax-SR subgroup (mean difference, 0.6 mm [95% CI, -0.3 to 1.6 mm]; $p = 0.06$). The highest ACL graft force reached a mean of 190.9 N in the pivot-shift (5-Nm) test.

Conclusions: The ACL reconstruction restored native kinematics and native rotational stability in all knees, including knees having laxity of secondary ligamentous restraints and clinically equivalent Grade-3 pivot-shift subluxation, and did so at ACL graft forces that were not excessive.

Clinical Relevance: An ACL reconstruction with a BPTB graft restored normal stability parameters regardless of the integrity of secondary ligamentous restraints.

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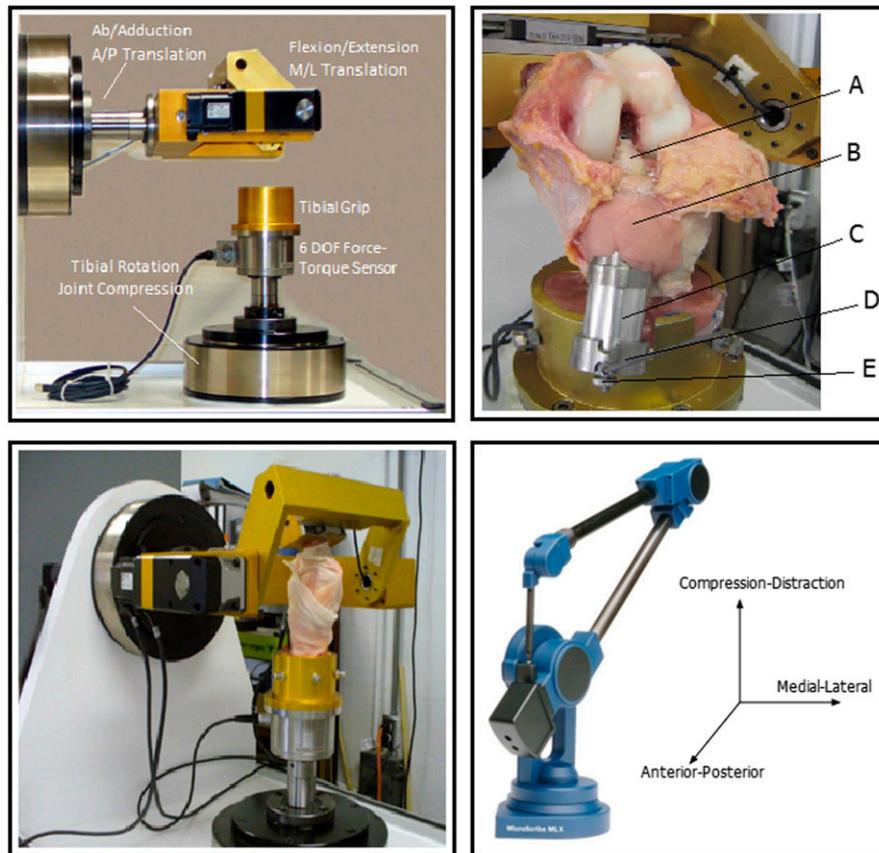


Fig. 1
The 2 left panels show different views of the robotic testing system, including the mechanical components (top left) and a view of a knee specimen during testing (bottom left). The graft tensioning system is shown in the top right panel. The tibial plug of the BPTB graft (**A**) is potted to a threaded rod that runs through the tibial tunnel and the entire construct, which includes the tibial adaptor that is adhered to the tibia with bone cement (**B**), metal spacer (**C**), and compression load cell (**D**). A polypropylene tube lines the interior of the tibial tunnel to allow free sliding of the graft construct. A thumb screw (**E**) is secured on the end of the threaded rod and is tightened to tension the graft. Finally, the bottom right panel displays the MicroScribe 3D coordinate digitizer and the coordinate system used during both digitization and testing. DOF = degrees of freedom, Ab = abduction, A/P = anterior-posterior, and M/L = medial-lateral.

To our knowledge, the ability of an anterior cruciate ligament (ACL) graft reconstruction to restore rotational stability in ACL-injured knees with laxity of secondary ligamentous restraints and severe anterior tibiofemoral compartment subluxation has not been determined. These unstable knees have been described in clinical studies as having a grossly positive Lachman test and Grade-3 pivot-shift anterior subluxation of such a magnitude that the tibia impinges against the lateral tibial plateau, resisting reduction¹. Biomechanical and clinical studies have noted that disruption of the lateral ligament structures (anterolateral ligament [ALL]¹⁻¹⁰ and iliotibial band [ITB]^{1,2,4,7,10-12}) with ACL injury results in markedly abnormal increases in lateral tibiofemoral compartment subluxation in pivot-shift, Lachman, and internal tibial rotation limit tests. In addition, high variability of knee specimens in the restraining function of the anterolateral structures has been reported^{9,10}, indicating that abnormal increases in compartment subluxation may occur not only with traumatic disruption but also with physiologic laxity of these

structures. The designation of physiologic laxity is synonymous with loss of resisting function or integrity of the secondary ligamentous restraints, and is the primary subject of this study.

Some authors have recommended a concurrent ALL or lateral extra-articular reconstruction in grossly unstable knees with ACL rupture and with laxity of secondary lateral ligamentous restraints¹³⁻¹⁷. However, other time-zero robotic studies have shown little effect of an ALL reconstruction in limiting

TABLE I Lax Secondary Restraint Criteria for Each Loading Condition

Lachman	Increase in center translation of ≥ 10 mm after ACL sectioning
Internal rotation	Intact internal rotation limit of $\geq 20^\circ$
Pivot Shifts 1 and 2	Absolute lateral compartment translation of ≥ 20 mm after ACL sectioning (Grade 3)

TABLE II Absolute Values of Tibial Translation (Center and Tibiofemoral Compartments), Degrees of Internal Rotation, and ACL Graft Force for Intact, ACL-Deficient, and ACL-Reconstructed States for Each Loading Condition*

Loading Profile and Test Condition	Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)	BPTB Graft Force (N)
Lachman (100 N anterior at 25° flexion)					
Intact	8.8 (7.7, 10.0)	6.6 (5.8, 7.4)	4.1 (2.7, 5.6)	7.0 (4.8, 9.2)	
ACL deficient	18.2 (16.6, 19.8)	17.6 (15.7, 19.4)	16.8 (14.4, 19.3)	2.2 (1.0, 3.3)	
ACL reconstructed	7.8 (6.3, 9.2)	6.6 (5.8, 7.5)†	5.4 (3.5, 7.3)	3.9 (0.8, 6.9)	144.5 (127.2, 161.7)
5 Nm IR at 25° flexion					
Intact	8.8 (7.8, 9.8)	2.2 (1.4, 3.0)	-4.3 (-5.4, -3.2)	20.2 (18.7, 21.6)	
ACL deficient	10.9 (9.3, 12.5)	3.9 (2.6, 5.3)	-2.9 (-4.3, -1.5)	21.4 (19.8, 23.0)	
ACL reconstructed	8.3 (7.2, 9.4) ‡	1.9 (1.1, 2.7)†	-4.7 (-5.9, -3.5)†	19.7 (18.3, 21.0)†	88.4 (60.6, 116.2)
Pivot Shift 1 (100 N anterior, 5 Nm IR, 7 Nm valgus)					
Intact	12.9 (11.8, 14.1)	6.2 (5.4, 7.0)	-0.4 (-1.6, 0.8)	20.6 (18.9, 22.2)	
ACL deficient	19.5 (17.9, 21.1)	13.5 (12.2, 14.7)	7.6 (6.1, 9.1)	18.3 (16.1, 20.5)	
ACL reconstructed	13.9 (12.7, 15.0)	7.1 (6.2, 7.9)	0.5 (-0.9, 1.8)	20.7 (18.9, 22.4)†	190.9 (155.6, 226.2)
Pivot Shift 2 (100 N anterior, 1 Nm IR, 7 Nm valgus)					
Intact	11.0 (9.8, 12.2)	6.4 (5.5, 7.2)	1.8 (0.4, 3.1)	13.9 (12.5, 15.3)	
ACL deficient	20.4 (18.8, 22.0)	16.9 (15.4, 18.4)	13.4 (11.4, 15.4)	10.6 (8.5, 12.7)	
ACL reconstructed	11.8 (10.5, 13.0)†	7.2 (6.3, 8.0)†	2.6 (1.1, 4.1)†	13.9 (12.0, 15.8)†	184.6 (164.9, 204.4)

*The values are given as the mean with the 95% confidence interval in parentheses. IR = internal rotation. †Indicates statistical equivalence: within 2 mm or 2° from the intact state, and $p < 0.05$.

abnormal pivot-shift subluxation^{8,9}. A question also arises with regard to the ability of an ACL graft to resist the abnormal increases in internal tibial rotation, as it is known that the native ACL functions along with the lateral extra-articular restraints in resisting abnormal internal tibial rotation^{2,5-7,10,18-20}.

An added issue of ACL reconstruction in Grade-3 pivot-shift-positive knees is the issue of the forces that occur in the ACL graft construct. It is possible that the ACL graft may

provide a stabilizing function in resisting abnormal knee displacements, but at the expense of deleterious graft forces that risk subsequent graft elongation and failure²¹.

Two important points of the present study require emphasis. First, the robotic simulation of the pivot-shift in this study involves a 4-degree-of-freedom loading profile of anterior tibial translation, internal tibial rotation, and valgus loading with flexion-extension, to induce maximum anterior subluxation of

TABLE III Absolute Values of Tibial Translation (Center and Tibiofemoral Compartments) and Degrees of Internal Rotation for Intact, ACL-Deficient, and ACL-Reconstructed States in the Lachman Test with Specimens Divided into Lax Secondary Restraints and Intact Secondary Restraints Subgroups

Test Condition	Lax Secondary Restraints* (N = 13)			
	Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
Intact	8.6 (7.1, 10.2)	7.1 (6.2, 7.9)	5.2 (3.2, 7.2)	6.2 (2.7, 9.6)
ACL deficient	20.2 (18.7, 21.7)†	20.2 (18.9, 21.5)†	20.1 (18.0, 22.2)†	1.2 (-0.2, 2.6)
ACL reconstructed	7.3 (5.0, 9.5)	7.2 (6.1, 8.4)‡	7.1 (4.3, 9.8)	1.9 (-2.8, 6.5)†

*The values are given as the mean, with the 95% confidence interval in parentheses. †Indicates statistical difference between subgroups ($p < 0.05$). ‡Indicates statistical equivalence: within 2 mm or 2° from the intact state of the same subgroup, and $p < 0.05$.

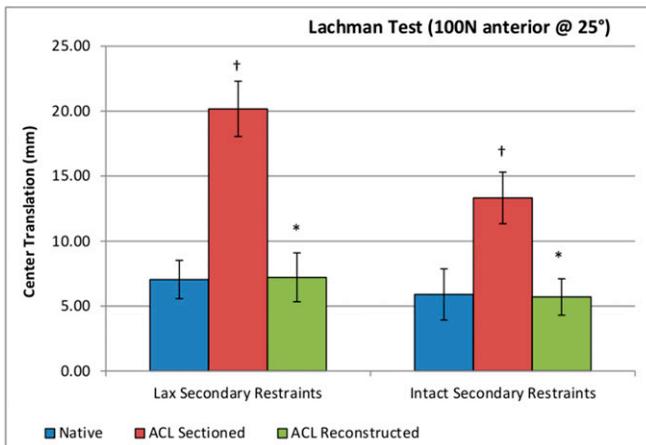


Fig. 2

Fig. 2 The mean anterior translation of the central compartment for native, ACL-sectioned, and ACL-reconstructed states under a 100-N anterior load at 25° of knee flexion (simulated Lachman test). The 2 subgroups are shown for lax and intact secondary restraints. The bars indicate the standard deviation. The ACL-reconstructed state was statistically equivalent to the native condition in both subgroups. The increase in translation after ACL sectioning in the Lax-SR subgroup was significantly greater than in the Intact-SR subgroup. *Statistical equivalence compared with native state ($p < 0.05$). †Significant difference compared with native state ($p < 0.05$). **Fig. 3** The mean ACL BPTB graft forces under the specified loading conditions for Lax-SR and Intact-SR knees are shown. The bars indicate the standard deviation. There was no significant difference in force between subgroups for any loading condition. IR = internal rotation.

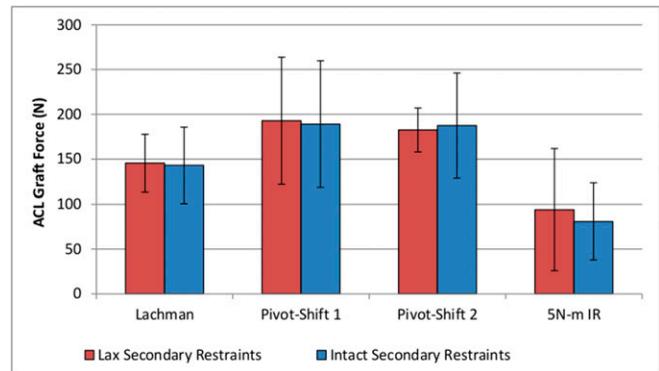


Fig. 3

both tibiofemoral compartments as the knee approaches full extension. A criticism of prior publications simulating the pivot shift has been the use of a loading profile of internal tibial rotation and valgus rotation, but with an absence of anterior loading. The internal rotation torque acting alone prevents anterior subluxation of the medial tibiofemoral compartment, with resulting decreases in maximum anterior tibial subluxation^{22,23}. Secondly, the implantation of an instrumented ACL graft allows the direct measurement of ACL graft forces under robotic loading conditions and avoids indirect superimposition of robotic calculations that may be subject to error²⁴.

The first hypothesis of this study was that an ACL graft placed in the central two-thirds of the native ACL femoral and tibial attachment sites will restore ACL function in resisting abnormal tibiofemoral compartment translations and rotations in the pivot-shift, Lachman, and internal tibial rotation loading tests in knees with and without physiologic laxity of secondary ligamentous restraints.

The second hypothesis was that the ACL reconstruction, under the above robotic loading conditions, functions under graft loads that are not so excessive as to risk subsequent graft elongation and failure.

Materials and Methods

Twenty-one fresh-frozen cadaver knee specimens (6 paired mean donor age (and standard deviation) was 55 ± 15 years (range, 23 to 79 years). Specimens were prepared as previously described^{23,25,26}. Before testing, the specimens were digitized with a 3-dimensional (3D) coordinate digitizer (MicroScribe G2; Revware) (Fig. 1) to locate the anatomic center of the tibial plateau at a point equidistant between the medial and lateral tibial spines and to determine its position relative to the tibial rotation axis of the robot. Medial and lateral compartment translations were measured at points located at 25% and 75% of the tibial plateau width^{22,23}.

TABLE III (continued)

Intact Secondary Restraints* (N = 8)			
Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
9.2 (7.2, 11.2)	5.9 (4.2, 7.6)	2.3 (0.7, 4.0)	8.4 (6.5, 10.2)
15.0 (13.0, 17.0)†	13.3 (11.6, 15.0)* †	11.5 (9.2, 13.9)†	3.8 (2.1, 5.5)
8.5 (6.7, 10.4)‡	5.7 (4.5, 6.9)‡	2.7 (1.5, 3.9)‡	7.1 (5.1, 9.2)†

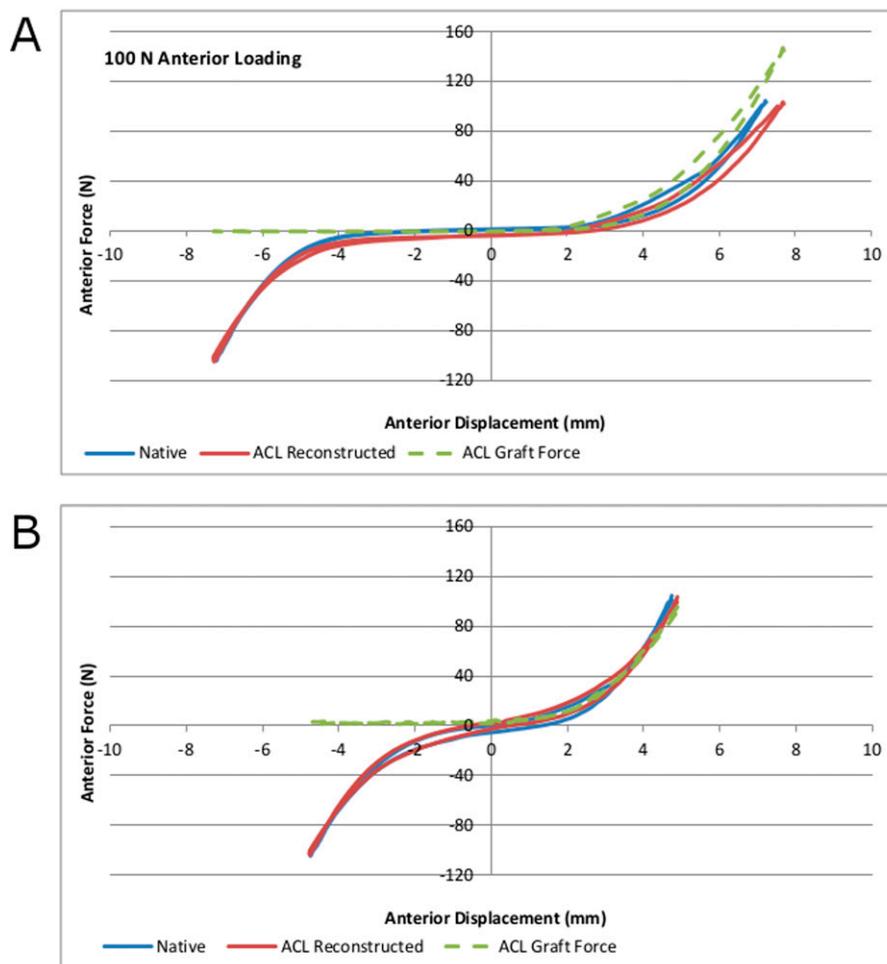


Fig. 4

Load-displacement curves in the simulated Lachman test (100-N anterior load at 25° of flexion) for a representative Lax-SR specimen (**Fig. 4-A**) and Intact-SR specimen (**Fig. 4-B**) are shown. Note that the ACL reconstruction restored central translation in both specimens and that the stiffness matches that of the native knee. The major difference between specimens is represented by the primary laxity region before the onset of resistance provided by the graft, which is approximately 4 mm in the Lax-SR specimen compared with 2 mm in the Intact-SR specimen.

Testing was conducted with a custom 6-degree-of-freedom robot²⁷ (Fig. 1). Its components, operation, and accuracy have been previously described^{23,25,26}.

Specimens were tested for 3 states: native, ACL deficient, and ACL reconstructed. Five loading profiles were used: the Lachman test (100-N anterior load and 25° of knee flexion), anterior limit test (100-N anterior load across a flexion range from 10° to 90°), internal rotation test (5-Nm internal rotation torque and 25° of knee flexion), Pivot Shift 1 (100-N anterior load, 5-Nm internal rotation, and 7-Nm valgus), and Pivot Shift 2 (100-N anterior load, 1-Nm internal rotation, and 7-Nm valgus). Pivot-shift displacement values were calculated at 25° of knee flexion as previously described^{23,25,26}.

The ACL reconstruction consisted of a 10-mm bone-patellar tendon-bone (BPTB) graft placed in the central two-thirds of the ACL tibial and femoral attachments, as previously described²⁶. Femoral fixation was achieved with a 9-mm metallic interference screw. Tibial fixation was achieved through

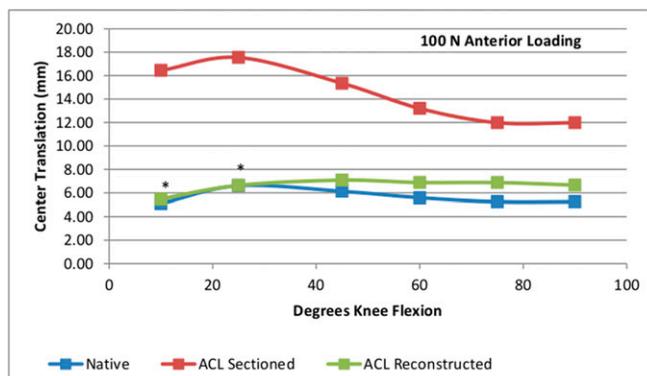


Fig. 5

Anterior limit curve of all 21 knees, showing central translation for native, ACL-sectioned, and ACL-reconstructed states under 100-N anterior loading between 10° and 90° of knee flexion. Note the small increase in translation of the ACL reconstruction at higher degrees of knee flexion, also shown in a previous study²⁶. *Statistical equivalence compared with native state ($p < 0.05$).

an external mounted construct that allowed for tensioning and direct measurement of ACL graft forces²⁶ (Fig. 1). The ACL graft was preloaded in the same manner as the native knees with 3 cycles of a constant 135-N anterior load held for 3 minutes. Residual graft elongation was determined by subtracting the end displacement from the initial displacement. It was determined that, after the third cycle, the graft elongated only a mean of 0.6 ± 0.3 mm, indicating that the graft was sufficiently preconditioned.

After testing, the data were first analyzed for all specimens together. Next, the specimens were divided into 2 subgroups on the basis of the translation and tibial rotation measurements under specific loading conditions. One subgroup represented specimens categorized as having intact secondary anterolateral restraints (the Intact-SR group). A second subgroup of specimens was categorized as having physiologic laxity (loss of integrity) of the secondary anterolateral restraints (the Lax-SR group). The subgroup conditions (Intact-SR and Lax-SR) were defined for the Lachman, internal rotation, and pivot-shift tests (Table I) on the basis of in vitro ligament studies, in which the abnormal motion limits and translations were determined after sectioning of anterolateral structures produced a loss of resisting function^{4,5,7,10}. This allowed a division into knees with and without integrity of the secondary ligamentous restraints. Specimens in this study that exceeded these rotation and translation limits were categorized as Lax-SR for the respective loading conditions, and represented the same laxities in knees with documented sectioning and loss of the anterolateral structures. Additionally, for the criterion for the pivot-shift tests

(Table I), publications on tibiofemoral lateral compartment translations of Grade-3 pivot-shift tests were also utilized^{1,28}.

Statistical Methods

Statistical equivalence was determined between native and ACL-deficient states and between native and ACL-reconstructed states for all specimens, and for the Lax-SR and Intact-SR specimens in each loading condition, using a repeated-measures analysis of variance (ANOVA) and equivalence testing using the two 1-sided t-test (TOST) method. This process and its advantages have been previously described²⁶. Equivalence testing was selected on the basis of recommendations in prior studies²⁹⁻³¹. The equivalence limits of 2 mm (difference in translation) and 2° (difference in internal rotation) were selected on the basis of a study that found that >95% of ACL injuries differ in translation by at least 3 mm from the native state³², as well as studies that noted mean increases in internal rotation of 1.6° and 1.5° after ACL sectioning^{25,26}. A p value of <0.05 was defined as statistically equivalent, and values are reported as mean differences with either 95% confidence intervals (CIs) or standard deviations, where appropriate.

Results

Lachman Test (100-N Anterior Load and 25° of Flexion)

After ACL sectioning, center translation increased by 10.9 mm (95% CI, 9.3 to 12.5 mm; $p = 0.99$) (Table II). After ACL reconstruction, center translation differed on average by 0.0 mm (95% CI, -0.4 to 0.4 mm) from that of the native state. Center translation after ACL reconstruction satisfied the

TABLE IV Absolute Values of Tibial Translation (Center and Tibiofemoral Compartments) and Degrees of Internal Rotation for Intact, ACL-Deficient, and ACL-Reconstructed States in the Internal Rotation Test with Specimens Divided into Lax Secondary Restraints and Intact Secondary Restraints Subgroups

Test Condition	Lax Secondary Restraints* (N = 13)			
	Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
Intact	9.0 (7.5, 10.4)	2.0 (0.7, 3.3)	-4.8 (-6.5, -3.1)	22.3 (21.3, 23.2)
ACL deficient	11.2 (8.9, 13.6)	3.9 (1.7, 6.1)	-3.2 (-5.5, -0.9)	23.5 (22.2, 24.8)
ACL reconstructed	8.2 (6.6, 9.8)†	1.7 (0.4, 2.9)†	-5.3 (-7.1, -3.5)†	21.4 (20.2, 22.6)†

*The values are given as the mean, with the 95% confidence interval in parentheses. †Indicates statistical equivalence: within 2 mm or 2° from the intact state of the same subgroup, and $p < 0.05$. There was no statistical difference between subgroups.

TABLE IV (continued)

Intact Secondary Restraints* (N = 8)			
Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
8.5 (6.9, 10.1)	2.4 (1.7, 3.1)	-3.6 (-4.7, -2.4)	16.8 (15.3, 18.3)
10.6 (8.4, 12.7)	3.6 (1.6, 5.6)†	-3.1 (-5.1, -1.0)†	17.9 (16.1, 19.7)
8.4 (6.4, 10.5)†	2.3 (1.4, 3.3)†	-3.7 (-4.8, -2.6)†	16.9 (15.2, 18.5)†

TABLE V Absolute Values of Tibial Translation (Center and Tibiofemoral Compartments) and Degrees of Internal Rotation for Intact, ACL-Deficient, and ACL-Reconstructed States in the Pivot Shift-1 Test with Specimens Divided into Lax Secondary Restraints and Intact Secondary Restraints Subgroups

Test Condition	Lax Secondary Restraints* (N = 8)			
	Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
Intact	14.7 (12.9, 16.4)	6.6 (5.3, 7.9)	-1.3 (-3.2, 0.7)	22.9 (20.7, 25.1)
ACL deficient	22.4 (20.7, 24.0)†	15.1 (13.8, 16.3)†	7.9 (5.7, 10.0)†	20.7 (16.4, 25.0)
ACL reconstructed	15.3 (13.4, 17.2)	7.2 (6.1, 8.2)‡	-0.8 (-2.1, 0.5)‡	23.3 (21.1, 25.4)‡

*The values are given as the mean, with the 95% confidence interval in parentheses. †Indicates statistical difference between subgroups ($p < 0.05$). ‡Indicates statistical equivalence: within 2 mm or 2° from the intact state of the same subgroup, and $p < 0.05$.

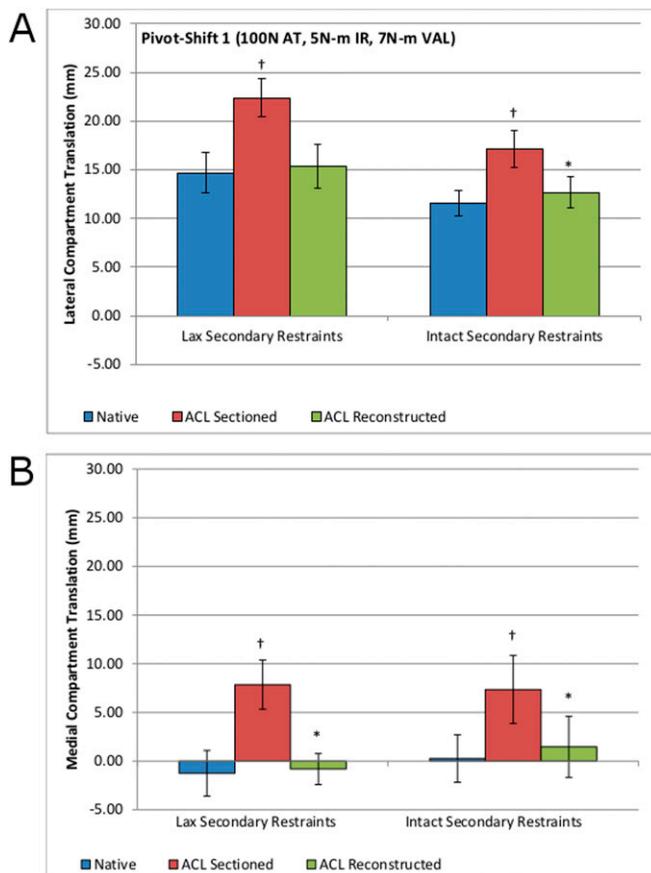


Fig. 6
The mean anterior translation of the lateral (**Fig. 6-A**) and medial tibiofemoral (**Fig. 6-B**) compartments for native, ACL-sectioned, and ACL-reconstructed states under Pivot Shift-1 loading (100-N anterior force, 5-Nm internal rotation [IR], and 7-Nm valgus [VAL]). Lax-SR and Intact-SR knees are represented. The bars indicate the standard deviation. In the ACL-reconstructed state, lateral compartment translation was statistically equivalent to the native condition in the Intact-SR subgroup, while medial compartment translation was statistically equivalent to the native condition in both subgroups. The increase in translation after ACL sectioning in the Lax-SR subgroup was significantly greater than that in the Intact-SR subgroup in both the lateral and medial compartments. *Statistical equivalence compared with native state ($p < 0.05$). †Significant difference compared with native state ($p < 0.05$).

equivalency criterion of being within 2 mm of the native state ($p = 0.0013$) (Table II). At the peak anterior load of 100 N, the force in the ACL graft measured 144.5 N (95% CI, 127.2 to 161.7 N).

In the Lax-SR subgroup, ACL sectioning produced an increase in center translation of 13.1 mm (95% CI, 11.7 to 14.5; $p = 0.99$) (Table III, Fig. 2). This was equivalent to the native state (difference of 0.2 mm [95% CI, -0.5 to 0.8 mm; $p = 0.03$]). Compared with the Lax-SR subgroup, ACL sectioning of the Intact-SR knees produced smaller increases (7.4 mm; 95% CI, 5.8 to 9.0 mm; $p = 0.99$) in center translation (Table III, Fig. 2). After ACL reconstruction, center translation was equivalent to the native state (difference of only -0.2 mm [95% CI, -0.8 to 0.4 mm; $p = 0.002$]). ACL graft force in the Lax-SR knees was 145.5 N (95% CI, 123.8 to 167.1 N), while the ACL graft force in the Intact-SR knees was 143.1 N (95% CI, 107.6 to 178.6 N) (Fig. 3). Figure 4 shows a force-displacement curve for a representative Lax-SR and a representative Intact-SR knee.

Anterior Limit Testing (100-N Anterior Load from 10° to 90° of Flexion)

Across the range of flexion, the greatest increase in center translation with the ACL sectioned occurred at 25° of flexion, while the smallest increase occurred at 75° and 90° of flexion. ACL reconstruction restored center translation at 10° and 25° of flexion to within 2 mm of that for the native state ($p < 0.05$) (Fig. 5). Four of 21 specimens showed increased center translation of >3 mm (range, -1.5 to 4.9 mm) at 90° of flexion. ACL graft forces measured a mean of 166.6 N (95% CI, 149.1 to 184.2 N), and decreased with flexion, measuring a mean of 89.8 N (95% CI, 65.2 to 114.4 N) at 90°.

Internal Rotation Test (5 Nm and 25° of Flexion)

There was a slight increase in internal rotation of 1.2° (95% CI, 0.7° to 1.7°; $p = 0.11$) when the ACL was sectioned that was not equivalent to the native state (Table II). This increase was restored to within 2° of the native state following the ACL reconstruction (a difference of -0.5° [95% CI, -1.0° to 0.0°]; $p = 0.012$). The ACL graft force following reconstruction averaged 88.4 N (95% CI, 60.6 to 116.2 N) under the 5-Nm torque.

TABLE V (continued)

Intact Secondary Restraints* (N = 10)			
Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
11.6 (10.6, 12.5)	5.8 (4.7, 6.9)	0.3 (-1.5, 3.0)	18.7 (16.8, 20.6)
17.2 (15.8, 18.5)†	12.2 (10.5, 13.9)†	7.4 (4.9, 9.9)†	16.5 (14.4, 18.5)
12.7 (11.5, 13.9)‡	7.0 (5.5, 8.5)‡	1.5 (-0.8, 3.7)‡	18.6 (16.6, 20.6)‡

In both Lax-SR and Intact-SR subgroups, the increase in internal rotation after ACL sectioning was minimal, measuring 1.3° (95% CI, 0.5° to 2.0°; $p = 0.06$) and 1.1° (95% CI, 0.5° to 1.7°; $p = 0.4$), respectively (Table IV). Internal rotation in both subgroups satisfied the equivalency criterion of being within 2° of the native state following ACL reconstruction ($p < 0.05$). The ACL graft force in Lax-SR knees averaged 93.9 N (95% CI, 48.2 to 139.6 N), whereas the ACL graft force in Intact-SR knees averaged 80.8 N (95% CI, 45.0 to 116.6 N) (Fig. 3).

Pivot Shift 1 (100-N Anterior Load, 5-Nm Internal Rotation, 7-Nm Valgus, and 25° of Flexion)

After ACL sectioning, lateral and medial compartment translation increased 6.5 mm (95% CI, 5.3 to 7.7 mm; $p = 0.99$) and 8.0 mm (95% CI, 6.7 to 9.3 mm; $p = 0.99$), respectively (Table II). Internal rotation decreased by 2.2° (95% CI, -3.6° to -0.8°; $p = 0.31$). Following the ACL reconstruction, lateral and medial compartment translation differed from the native state values by only 0.9 mm (95% CI, 0.4 to 1.4 mm; $p = 0.055$) and 0.9 mm (95% CI, 0.3 to 1.4 mm; $p = 0.053$), respectively, while internal rotation differed from that of the native state by only 0.1° (95% CI, -0.5° to 0.7°; $p = 0.0021$). The ACL graft force under the combined Pivot Shift-1 loading averaged 190.9 N (95% CI, 155.6 to 226.2 N).

In Lax-SR knees, lateral and medial compartment translation increased by 7.7 mm (95% CI, 5.3 to 10.1 mm; $p = 0.99$) and 9.1 mm (95% CI, 6.4 to 11.8 mm; $p = 0.99$), respectively, with the ACL sectioned (Table V, Fig. 6). These compare with increases of 5.6 mm (95% CI, 4.5 to 6.7 mm; $p = 0.99$) and 7.1 mm (95% CI, 5.8 to 8.4 mm; $p = 0.99$) in the Intact-SR knees. Lateral and medial compartment translations in the Lax-SR knees were restored to within 0.6 mm (95% CI, -0.3 to 1.6 mm; $p = 0.06$) and 0.4 mm (95% CI, -0.6 to 1.5 mm; $p = 0.04$) of the native state, respectively. Corresponding values for the Intact-SR knees were 1.1 mm (95% CI, 0.5 to 1.8 mm; $p = 0.03$) and 1.2 mm (95% CI, 0.4 to 2.0 mm; $p = 0.04$), respectively (Table V). The ACL graft force was similar between subgroups, averaging 192.9 N (95% CI, 133.6 to 252.2 N) in the Lax-SR knees and 189.1 N (95% CI, 134.8 to 243.5 N) in the Intact-SR knees.

Pivot Shift 2 (100-N Anterior Load, 1-Nm Internal Rotation, 7-Nm Valgus, and 25° of Flexion)

After ACL sectioning, lateral and medial compartment translation increased by 9.4 mm (95% CI, 8.0 to 10.8 mm; $p = 0.99$)

and 11.6 mm (95% CI, 9.9 to 13.3 mm; $p = 0.99$), respectively (Table II). Internal rotation decreased by 3.3° (95% CI, -5.0° to -1.6°; $p = 0.97$). Following the ACL reconstruction, lateral and medial compartment translation differed from native state values by only 0.8 mm (95% CI, 0.2 to 1.3 mm; $p = 0.028$) and 0.8 mm (95% CI, 0.3 to 1.4 mm; $p = 0.032$), respectively. Internal rotation on average differed from that of the native state by 0.0° (95% CI, -1.0° to 0.9°; $p = 0.0013$). The measured ACL graft force under the combined Pivot Shift-2 loading averaged 184.6 N (95% CI, 164.9 to 204.4 N).

In the Lax-SR knees, lateral and medial compartment translations increased by 10.6 mm (95% CI, 8.5 to 12.8 mm; $p = 0.99$) and 13.0 mm (95% CI, 10.3 to 15.7 mm; $p = 0.99$), respectively, following ACL sectioning (Table VI). These compare with corresponding increases of 7.8 mm (95% CI, 6.3 to 9.4 mm; $p = 0.99$) and 10.0 mm (95% CI, 8.3 to 11.7 mm; $p = 0.99$) in the Intact-SR knees. In the Lax-SR knees, lateral and medial compartment translations were restored to within 0.5 mm (95% CI, -0.3 to 1.3 mm; $p = 0.047$) and 0.5 mm (95% CI, -0.4 to 1.4 mm; $p = 0.047$) of the native state, respectively. Corresponding restorations for the Intact-SR knees were to within 1.1 mm (95% CI, 0.4 to 1.9 mm; $p = 0.06$) and 1.3 mm (95% CI, 0.5 to 2.0 mm; $p = 0.08$) of the native state, respectively (Table VI). Figure 7 shows a compartment map for 2 representative specimens (1 Lax-SR and 1 Intact-SR) at each cutting state. The ACL graft force was again similar between subgroups, averaging 182.6 N (95% CI, 166.1 to 199.0 N) in the Lax-SR knees and 187.5 N (95% CI, 138.4 to 236.6 N) in the Intact-SR knees.

Discussion

The results of this study affirmed our first hypothesis, which was that an ACL graft placed in the central femoral and tibial attachment sites restores ACL function in resisting the pivot-shift, Lachman, and internal tibial rotation loading tests (Table II). Lateral compartment translation in the ACL-reconstructed knee for the pivot-shift tests differed from that of the native state by ≤ 0.9 mm. Center translation in the Lachman was restored to that of the native state (equivalent, $p = 0.0013$), while internal rotation in the 5-Nm internal rotation test was restored to within -0.5° of the native state (equivalent, $p = 0.012$). The data in this study, as applied to in vivo ACL surgery, showed that an ACL graft that is sufficiently tensioned to restore normal anterior displacement in the Lachman test will also fully resist the abnormal subluxations in the pivot-shift tests.

TABLE VI Absolute Values of Tibial Translation (Center and Tibiofemoral Compartments) and Degrees of Internal Rotation for Intact, ACL-Deficient, and ACL-Reconstructed States in the Pivot Shift-2 Test with Specimens Divided into Lax Secondary Restraints and Intact Secondary Restraints Subgroups

Test Condition	Lax Secondary Restraints* (N = 11)			
	Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
Intact	12.2 (10.3, 14.1)	6.7 (5.6, 7.8)	1.1 (-0.5, 2.8)	15.2 (13.2, 17.1)
ACL deficient	22.9 (21.4, 24.3)†	18.5 (17.0, 20.0)†	14.1 (11.4, 16.8)†	11.7 (8.1, 15.2)
ACL reconstructed	12.7 (10.6, 14.8)‡	7.4 (6.3, 8.0)‡	1.6 (0.3, 2.9)‡	15.2 (12.2, 18.2)‡

*The values are given as the mean, with the 95% confidence interval in parentheses. †Indicates statistical difference between subgroups ($p < 0.05$). ‡Indicates statistical equivalence: within 2 mm or 2° from the intact state of the same subgroup, and $p < 0.05$.

Similarly, when the specimens were divided into subgroups having lax compared with intact secondary restraints, ACL reconstruction restored native ACL kinematics under the robotic

loading conditions of this study without overconstraining the joint (Tables III through VI). The data show that an ACL reconstruction resists pivot-shift subluxation in clinically equivalent Grade-3

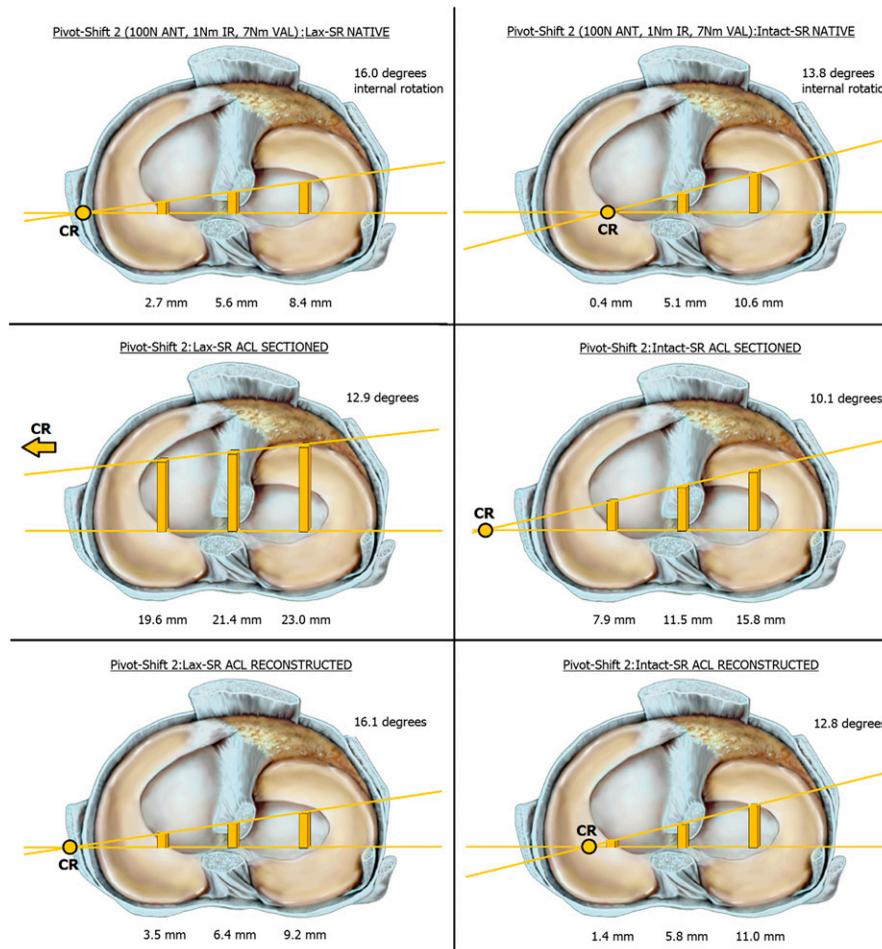


Fig. 7

Compartment maps of a representative Lax-SR specimen (left panels) and a representative Intact-SR specimen (right panels) under Pivot Shift-2 loading (100-N anterior [ANT], 1-Nm internal rotation [IR], and 7-Nm valgus [VAL]) for native, ACL-sectioned, and ACL-reconstructed states. Specimens are right knees with the medial compartment on the left and lateral compartment on the right. The center of rotation is labeled as CR. Note the large shift of the CR in the Lax-SR knee with the ACL sectioned, and the difference in both absolute magnitude and increases in compartment translations. Also note that the ACL reconstruction successfully restored the gross subluxations to native kinematics. This restoration was also observed in the Intact-SR specimen.

TABLE VI (continued)

Intact Secondary Restraints* (N = 9)			
Lateral Compartment (mm)	Center (mm)	Medial Compartment (mm)	Internal Tibial Rotation (deg)
9.5 (8.4, 10.5)	6.0 (4.5, 7.4)	2.6 (0.0, 5.1)	12.4 (10.5, 14.4)
17.3 (15.9, 18.8)†	14.9 (12.6, 17.2)†	12.6 (9.1, 16.0)†	9.3 (7.1, 11.5)
10.6 (9.2, 12.0)	7.2 (5.2, 9.1)	3.8 (0.8, 6.9)	12.3 (9.9, 14.7)‡

pivot-shift knees with physiologic laxity or with functionally deficient secondary ligamentous restraints^{1,28,33}.

The results of this study also affirmed the second hypothesis, which was that the ACL graft forces were not potentially deleterious under the applied loading conditions. Even for the pivot-shift loading condition, which elicited the highest ACL graft force, that force was still less than one-half of BPTB fixation strengths for metallic interference screws, which have been reported to be in the range of 435.0 to 558.3 N^{34,35}. It is important to note that the ACL graft forces in the present study were based on direct ACL graft measurements, and thus arguably are more reliable than ACL graft forces indirectly calculated from robotic superimposition algorithms²⁴. In the present study, the in situ ACL graft forces in the Lachman and Pivot Shift-1 tests averaged 144.5 N and 190.9 N, respectively, compared with 63.7 N and 36.4 N, respectively, in these tests in the robotic study by Araujo et al.³⁶ The low ACL graft loads in simulated pivot-shift tests may have arisen in that study because it did not include anterior tibial loading to accompany the internal rotation and valgus loading inputs of the robot.

Initial robotic studies³⁷⁻³⁹ on ACL function often employed a single-bundle hybrid graft placement with a proximal femoral anteromedial (AM) to tibial posteromedial (PM) construct, with comparisons being made with a double-bundle ACL graft construct. Those studies contributed to the initial misconception that a single-strand ACL graft would not restore rotational knee stability. Subsequently, studies on ACL single-graft constructs that selected a femoral-AM to tibial-AM or a femoral-tibial mid-mid position within the ACL attachment noted ACL graft function that more closely replicated native ACL kinematics^{15,26,40,41}. The results of the present study show that an ACL graft that simulates AM bundle function restores rotational knee stability in addition to restoring Lachman simulated tests in vitro^{26,42}. There is concern that operative procedures to place an “anatomic” ACL graft may err in placing a femoral graft within the distal posterolateral bundle portion, placement that is not ideal⁴². A recommendation for more reliably locating the ACL femoral anatomic attachment at the time of arthroscopy is to place the knee in approximately 20° to 30° of flexion rather than 90°, since the latter can obscure visualization of the proximal ACL attachment. With slight knee flexion, the ACL attachment proximal-distal and anterior-posterior landmarks are easily identified, facilitating location of the guide pin at the junction of the

proximal and middle one-thirds within the central attachment⁴³. A prior study showed that the ACL reconstruction did not provide a complete enough restraint to avoid small increases in internal rotation at high degrees of flexion in knees with loss of the anterolateral capsular structures (ALL and ITB)³³. Residual increases in internal rotation of 5.1° and 6.4° were reported at 60° and 90° of flexion (5 Nm of internal rotation). A properly tensioned ALL reconstruction, along with an ACL reconstruction, may correct these small internal rotation deficits. However, ALL reconstruction does not resist pivot-shift subluxations³³.

It is well recognized that the pivot-shift anterior tibial subluxation corresponds to patients' instability symptoms. Accordingly, ACL graft behaviors are defined by the ability to resist induced pivot-shift subluxations. The loading profile typically used in published pivot-shift cadaveric studies involves valgus and internal rotation inputs, without including an anterior tibial loading component. However, this third loading component is necessary to induce the pivot-shift subluxation^{22,23}. In the absence of anterior loading, internal rotation torque constrains anterior tibial subluxation of the central and medial tibiofemoral compartments^{6,36,39,40} to one-half or less of the values induced in clinical Lachman tests. This correspondingly limits the reliability of conclusions drawn experimentally regarding ACL graft function.

There are limitations to the present study. The time-zero ACL graft effects and graft forces would be expected to change with biological remodeling. Moreover, such remodeling does not restore native ACL microgeometry or native ACL function. The importance of time-zero studies is to demonstrate that the ACL surgical reconstruction restores ACL function and that graft forces are not deleterious to the construct. The present data apply only to the use of a BPTB graft. Other ACL grafts or graft fixation techniques were not considered. This investigation was based on essentially perfect graft placement, which restricts any conclusions to this situation. Also, ACL forces for intact knees were not measured. Finally, robotic loading inputs in the present study were quasi-static and therefore do not fully simulate the dynamic in vivo knee loading conditions under which an ACL graft must function to provide knee stability.

In conclusion, an ideally positioned ACL reconstruction (BPTB) resists pivot-shift subluxations and abnormal anterior translations in knees both with and without integrity of the secondary ligamentous restraints. ■

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