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Knee Stability and Graft Function Following Anterior Cruciate Ligament Reconstruction: Comparison Between 11 O'clock and 10 O'clock Femoral Tunnel Placement

John C. Loh, M.D., Yukihisa Fukuda, M.D., Eiichi Tsuda, M.D., Richard J. Steadman, M.D., Freddie H. Fu, M.D., and Savio L-Y. Woo, Ph.D., D.Sc.

Purpose: To study how well an anterior cruciate ligament (ACL) graft fixed at the 10 and 11 o'clock positions can restore knee function in response to both externally applied anterior tibial and combined rotatory loads by comparing the biomechanical results with each other and with the intact knee. **Type of Study:** Biomechanical experiment using human cadaveric specimens. **Methods:** Ten human cadaveric knees (age, 41 ± 13 years) were reconstructed by placing a bone–patellar tendon–bone graft at the 10 and 11 o'clock positions, in a randomized order, and then tested using a robotic/universal force-moment sensor testing system. Two external loading conditions were applied: (1) 134 N anterior tibial load with the knee at full extension, 15°, 30°, 60°, and 90° of flexion, and (2) a combined rotatory load of 10 N-m valgus and 5 N-m internal tibial torque with the knee at 15° and 30° of flexion. The resulting kinematics of the reconstructed knee and in situ forces in the ACL graft were determined for each femoral tunnel position. **Results:** In response to a 134-N anterior tibial load, anterior tibial translation (ATT) for both femoral tunnel positions was not significantly different from the intact knee except at 90° of knee flexion as well as at 60° of knee flexion for the 10 o'clock position. There was no significant difference in the ATT between the 10 and 11 o'clock positions, except at 90° of knee flexion. Under a combined rotatory load, however, the coupled ATT for the 11 o'clock position was approximately 130% of that for the intact knee at 15° and 30° of flexion. For the 10 o'clock position, the coupled ATT was not significantly different from the intact knee at 15° of flexion and approximately 120% of that for the intact knee at 30° of flexion. Coupled ATT for the 10 o'clock position was significantly smaller than for the 11 o'clock position at 15° and 30° of flexion. The in situ force in the ACL graft was also significantly higher for the 10 o'clock position than the 11 o'clock position at 30° of flexion in response to the same loading condition (70 ± 18 N *v* 60 ± 15 N, respectively). **Conclusions:** The 10 o'clock position more effectively resists rotatory loads when compared with the 11 o'clock position as evidenced by smaller ATT and higher in situ force in the graft. Despite the fact that ACL grafts placed at the 10 or 11 o'clock positions are equally effective under an anterior tibial load, neither femoral tunnel position was able to fully restore knee stability to the level of the intact knee. **Key Words:** Anterior cruciate ligament—Reconstruction—Tunnel placement—Knee kinematics—In situ force.

From the Musculoskeletal Research Center, Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania; and Steadman◆Hawkins Sports Medicine Foundation, Vail, Colorado (R.J.S.), U.S.A.

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Address correspondence and reprint requests to Savio L-Y. Woo, Ph.D., D.Sc., Musculoskeletal Research Center, 210 Lothrop St, E1641-BST, PO Box 71199, Pittsburgh, PA 15213, U.S.A. E-mail: ddecenzo@pitt.edu

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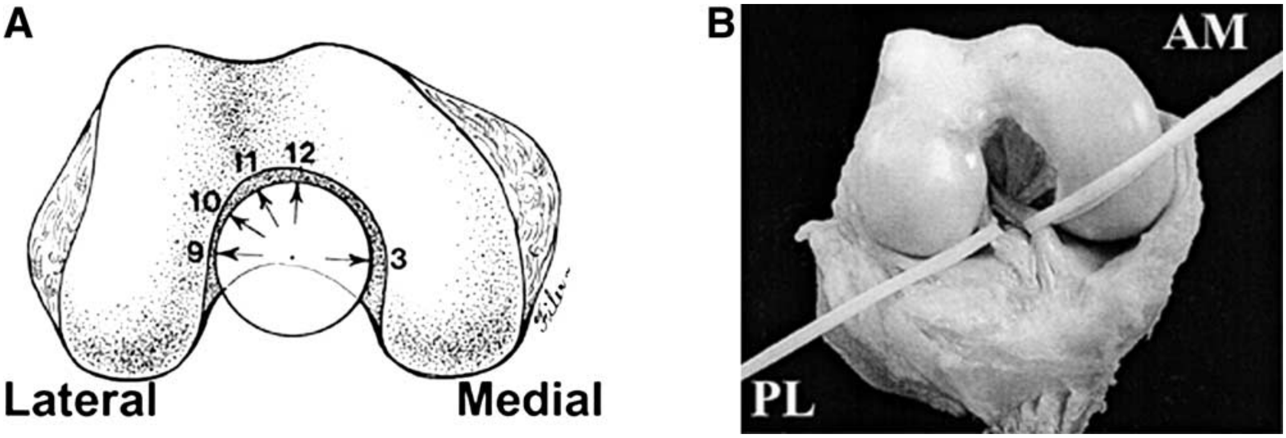

FIGURE 1. (A) The 10 o'clock and 11 o'clock positions of femoral tunnel placement for a right knee. (B) Photograph of the separated ACL bundles, AM and PL.

Anatomic studies of the anterior cruciate ligament (ACL) show 2 grossly distinguishable components, i.e., the anteromedial (AM) bundle and posterolateral (PL) bundle.[1-6] These 2 bundles exhibit a different pattern of changes in end-to-end fiber length during passive knee flexion and extension, with the AM bundle presenting a minimal change in length throughout the range of passive knee flexion and extension.[4,7] Such anatomic complexity of the ACL has not been reproduced by current ACL reconstruction procedures.[8] It has been popular to place the femoral bone tunnel at the so-called 11 o'clock position for the right knee (or 1 o'clock position for the left knee) (Fig 1A), in order to replicate the origin of the AM bundle of the ACL.[9] Studies have shown that this graft placement is quite sufficient at limiting anterior tibial translation (ATT) in response to anterior tibial loads such as those used in the Lachman or anterior drawer tests.[10]

Recent laboratory studies have clearly shown that there is an uneven distribution of forces between the AM and PL bundles of the ACL in response to externally applied loads.[11] When the knee is subjected to an anterior tibial load, two thirds of the total force in the ACL was carried by the PL bundle when the knee was near full extension. Further, when an ACL reconstructed knee was subjected to more complex rotatory loads that include valgus and axial tibial torques, the 11 o'clock position for graft placement became insufficient at limiting the coupled ATT.[10,12,13] Concomitantly, more lateral graft placement at the 10 o'clock position, which is anatomically closer to the femoral insertion of the posterolateral (PL) bundle (Fig 1B), has been advocated by some surgeons.[14,15] It is thought that such a lateralization would be able to improve the rotatory stability of the reconstructed knee.[10,12]

Thus, the objectives of this study were to (1) evaluate whether placing the ACL graft at the 10 o'clock or 11 o'clock positions would result in knee kinematics and in situ force in the graft closer to that of the intact knee, and (2) examine whether there is a difference in results between the 2 femoral tunnel positions when the knee is subjected to 2 external loading conditions: anterior tibial loading and combined rotatory loading of internal tibial and valgus torques. It was hypothesized that a knee with an ACL graft placed at the 10 o'clock position would respond similarly in response to an anterior tibial load compared with the 11 o'clock position, but would show an improvement in response to the combined rotatory load because the former graft is placed farther away from the center of knee rotation.[10] The 6-degree of freedom (DOF) knee kinematics and the in situ force in the ACL and ACL graft in response to externally applied loads were measured by a robotic/universal force-moment sensor (UFS) testing system and were used as the basis for the comparison.

METHODS

Ten fresh-frozen human cadaveric knees (age, 41 ± 13 years) were used for this study. Roentgenograms of specimens were taken and examined to ensure there was no evidence of bony abnormalities, deformities, or osteoarthritis. The knees were stored in airtight plastic bags at −20°C and thawed overnight at room temperature before testing.[16] The tibia and femur were

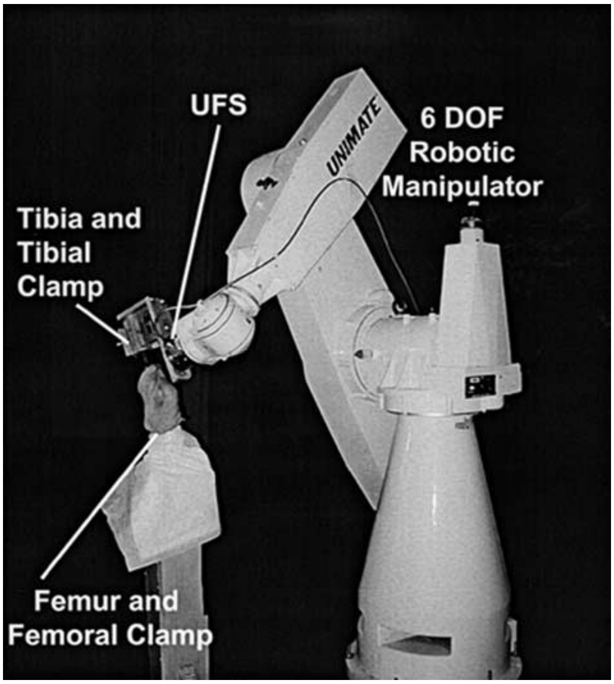

FIGURE 2. The robotic/universal force-moment sensor testing system with a cadaveric knee specimen.

then cut approximately 20 cm from the joint line. The skin and muscle more than 10 cm away from the joint line were removed so that the bones were exposed. A bone–patellar tendon–bone graft, 10-mm wide with 20-mm long bone plugs, was harvested from each knee and used as the ACL replacement graft. The femur and tibia were each secured within a 6-mm diameter aluminum cylinder using an epoxy compound (Bond-Tite Products, Cleveland, OH). The specimen was then mounted in a robotic/UFS testing system.[17-20] The femoral side was rigidly fixed relative to the base of the robotic manipulator (PUMA Model 726; Unimate Inc, Danbury, CT), while the tibial side was attached through the UFS (Model 4015; JR3 Inc, Woodland, CA) to the end-effector of the robotic manipulator (Fig 2).

The experimental protocol and data acquired are outlined in Fig 3. First the passive path of flexion/extension of the intact knee was determined in 1° increments by minimizing all the external forces and moments. This position was used to serve as the starting point during the ensuing experiments.[12,13,21] For this study, 2 external loading conditions were applied to the knee: (1) a 134-N anterior load was applied to the tibia with the knee at full extension, 15°, 30°, 60°, and 90° of flexion and (2) a combined 10 N-m valgus torque and 5 N-m internal tibial torque at

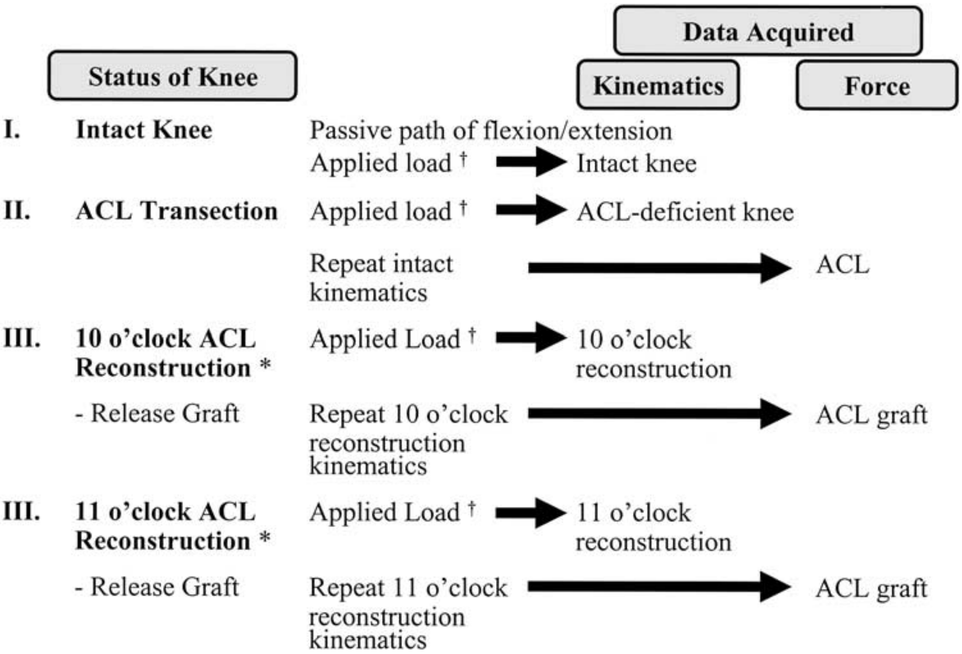

FIGURE 3. Experimental protocol and the data that were acquired. (*The order of 10 and 11 o'clock ACL reconstruction was randomized. †Two loading conditions were applied: (1) anterior tibial load and (2) combined rotatory load.

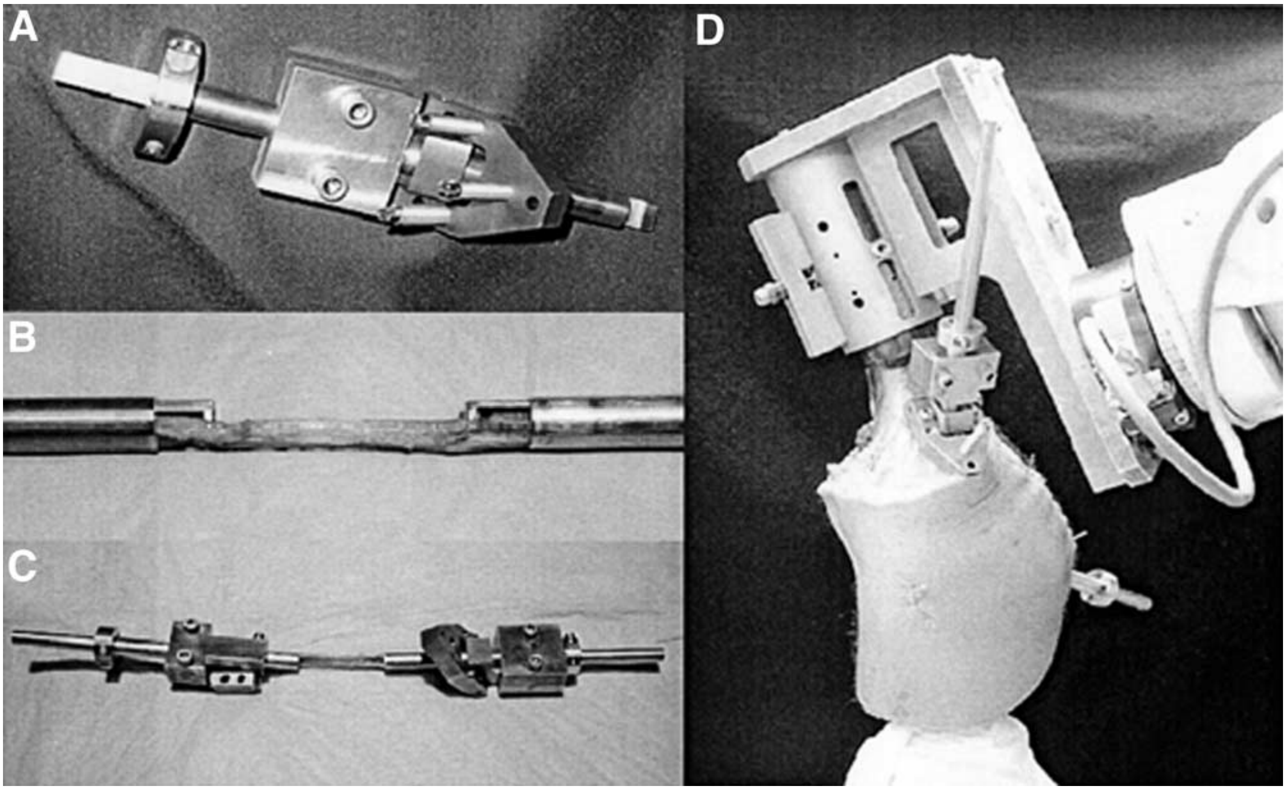

FIGURE 4. The custom-made fixation device consisting of (A) an outer sleeve, (B) inner hook, and (C) adjustable fixator. (D) Cadaveric knee with custom-made fixation device mounted on robotic/UFS testing system.

15° and 30° of flexion (combined rotatory load). The resulting 5-DOF kinematics of the intact knee, including anterior-posterior, medial-lateral, and proximal-distal translations, as well as internal-external and varus-valgus rotations, were determined.

The in situ force in the ACL, i.e., the tension that the ACL experiences in its anatomic position during knee motion, was determined by carefully transecting the ACL through a medial parapatellar arthrotomy. The previously recorded positions of the intact knee were repeated by the robotic manipulator on the ACL-deficient knee, while the UFS measured new forces and moments. Based on the principle of superposition, the vector difference between the forces of the intact and ACL-deficient knee was the in situ force in the ACL.[19] To assess changes in knee kinematics associated with ACL deficiency, the same external loads previously applied to the intact knee were again applied to the ACL-deficient knee and the resulting kinematics were measured.

Subsequently, the ACL reconstruction was performed on the same knee through a mini-arthrotomy. Tibial and femoral tunnels were placed in a routine fashion using commercially available drill guides (tibial: Protrac; Smith & Nephew, Andover, MA) (femoral: 7-mm offset guide; Arthrex, Naples, FL). For tibial tunnel placement, the tunnel was located in the middle third of the original ACL insertion site.[22] Both the 10 o'clock and 11 o'clock femoral tunnel placements were placed using a 7-mm offset drill guide, assuring that the posterior edge of the femoral tunnel was placed 2 mm anterior from the posterior edge of the intercondylar notch. The 11 o'clock femoral position was designed to approximate the AM bundle of the ACL and the 10 o'clock femoral position was designed to approximate the PL bundle of the ACL. These reconstructions were performed in a randomized order whereby half the specimens were reconstructed at the 10 o'clock position first and the other half were reconstructed at the 11 o'clock position first. Tibial and femoral fixation for the bone–patellar tendon–bone graft was achieved using a custom-made fixation device consisting of an outer sleeve, an inner hook, and an adjustable fixator (Fig 4). Use of this device enabled rigid fixation of the bone plug and prevented bone plug damage or bone tunnel enlarge-

Table 1. *Anterior Tibial Translation in Response to 134 N Anterior Tibial Load (Mean ± SD mm)*

Flexion Angle	Intact Knee	ACL-Deficient	ACL-Reconstructed Knee	
			11 o'clock	10 o'clock
Full Extension	5.1 ± 1.7	13.3 ± 3.6*	5.0 ± 1.9†	3.8 ± 1.5†
15°	6.4 ± 2.4	17.8 ± 3.5*	6.9 ± 2.9†	5.8 ± 2.4†
30°	7.1 ± 3.2	19.8 ± 4.9*	8.8 ± 4.3†	8.2 ± 3.7†
60°	7.4 ± 3.6	17.0 ± 6.8*	8.9 ± 3.8†	9.3 ± 3.8*†
90°	5.4 ± 3.3	11.6 ± 4.5*	7.0 ± 3.6*†	8.1 ± 3.6*†‡

*$P < .05$ compared with intact knee.
†$P < .05$ compared with ACL-deficient knee.
‡$P < .05$ compared with 11 o'clock reconstruction.

ment that would occur with direct fixation techniques such as an interference screw. Furthermore, fixation using this device allowed for consistent application of initial graft tension in both reconstructions. Each graft was preconditioned by moving the knee between 0° and 90° of knee flexion while applying a 44-N pretension to the graft for 5 cycles. During graft fixation, 67 N of posterior tibial load was applied at 30° of knee flexion and 44 N of initial graft tension was maintained.[23] Both external loading conditions were applied to reconstructions at both the 10 and 11 o'clock positions, and the 5-DOF kinematics were recorded. The graft was then removed and the previously recorded kinematics of the reconstructed knee were repeated in order to determine the in situ force in the ACL graft for both loading conditions.

Data on the 5-DOF knee kinematics obtained from 4 different knee states, i.e., the intact, ACL-deficient and ACL-reconstructed knees, as well as the in situ force in the ACL and the ACL grafts in response to both loading conditions, were analyzed. Because all variables were measured within each specimen, statistical analysis of the kinematics and in situ force was performed using a 2-factor repeated-measures analysis of variance. As a result, this analysis has the advantage of being very sensitive to relative changes occurring within an individual knee and the effects of specimen variability are minimized.[24] Multiple contrasts were performed to evaluate the effects of ACL reconstruction at specific angles of knee flexion. Statistical significance was set at $P < .05$.

RESULTS

Anterior Tibial Loading

In response to a 134-N anterior tibial load, the ATT for the intact knee ranged from 5.1 ± 1.7 mm to 7.4 ± 3.6 mm (Table 1). After ACL transection, these values significantly increased by 2- to 3-fold throughout the range of flexion angles tested, measuring 11.6 ± 4.5 mm to 19.8 ± 4.9 mm ($P < .05$). After ACL reconstruction, ATT decreased significantly from those for the ACL-deficient knee. For the 11 o'clock position, the ATT was found to be not significantly different from the intact knee except at 90° of knee flexion (7.0 ± 3.6 mm *v* 5.4 ± 3.3 mm, respectively, $P < .05$). For the 10 o'clock position, the results were similar to the intact knee except at 60° and 90° of knee flexion, where the ATT remained higher for the 10 o'clock position ($P < .05$). When comparing the ATT between the 2 femoral tunnel positions, significant differences were only detected at 90° of knee flexion, where the 10 o'clock positions had an average of 1.1 mm higher ATT than the 11 o'clock position ($P < .05$).

The coupled internal tibial rotation (ITR) in response to an anterior tibial load was small, ranging from 2.3° ± 3.8° to 4.2° ± 9.4° in the intact knee. For the ACL-deficient knee, coupled ITR was still small, ranging from 1.3° ± 8.6° to 3.0° ± 5.1°. After ACL reconstruction, coupled ITR remained small, ranging from 1.8° ± 3.2° to 5.4° ± 11.7°. For the 11 o'clock position coupled ITR ranged from 3.3° ± 4.8° to 6.0° ± 11.6° and 1.8° ± 3.2° to 5.4° ± 11.7° for the 10 o'clock position. Coupled valgus rotation of the intact knee was also small and greatest at 60° of knee flexion (1.6° ± 1.4°). For the ACL-deficient knee, coupled valgus rotation reached a maximum of 1.1° ± 1.7° at 30° of knee flexion. For the 11 and 10 o'clock positions, coupled valgus rotation reached a maximum of 2.2° ± 1.7° and 2.0° ± 1.9°, respectively, at 60° of knee flexion.

The data on the in situ force in the ACL and ACL graft in response to anterior tibial load are detailed in

TABLE 2. *In Situ Force in Response to 134 N Anterior Tibial Load (Mean ± SD N)*

		ACL Graft	
Flexion Angle	Intact ACL	11 o'clock	10 o'clock
Full Extension	97 ± 32	101 ± 25	105 ± 31
15°	133 ± 10	136 ± 14	135 ± 20
30°	133 ± 18	139 ± 22	135 ± 21
60°	103 ± 19	99 ± 28	91 ± 32*
90°	82 ± 15	80 ± 23	60 ± 25*†

*$P < .05$ compared with intact ACL.
†$P < .05$ compared with graft placed at 11 o'clock position.

Table 2. For the 11 o'clock position, no significant difference was found when compared to the intact ACL ($P > .05$). The same was true for the 10 o'clock position, with the exception that the in situ forces of the ACL graft at higher angles of knee flexion (60° and 90°) were significantly lower than those for the intact ACL ($P < .05$). Furthermore, the in situ forces in the ACL graft at the 10 o'clock position were not different from those at the 11 o'clock position except at 90° of knee flexion (60 ± 25 N *v* 80 ± 23 N, respectively, $P < .05$).

Combined Rotatory Loading

In response to a combined rotatory load, there was notable coupled ATT ranging from 3.6 ± 2.3 mm to 5.7 ± 3.6 mm for the intact knee (Table 3). The coupled ATT increased 2- to 3-fold (10.9 ± 2.8 mm to 12.3 ± 3.9 mm) following ACL transection ($P < .05$). With reconstruction, the coupled ATT significantly decreased in comparison with the ACL-deficient knee ($P < .05$). In the case of the 11 o'clock position, the coupled ATT remained significantly higher, at approximately 130% of the intact knee ($P < .05$), whereas for the 10 o'clock position, the coupled ATT was not significantly different from those for the intact knee at 15° of knee flexion ($P > .05$) but remained at approximately 120% higher at 30° of knee flexion ($P < .05$). More interestingly, coupled ATT for the 10 o'clock position was significantly smaller at both 15° and 30° of knee flexion when compared with those for the 11 o'clock position ($P < .05$).

The ITR in response to a combined rotatory load was 16.1° ± 8.3° at 15° of flexion and 20.6° ± 11.1° at 30° of knee flexion for the intact knee (Table 3). It should be noted that these values were much higher, more than 5-fold, than those during anterior tibial loading, where the ITR was less than 3.5°. For the 11 o'clock position, ITR remained larger than that for the intact knee at both 15° and 30° of knee flexion (17.3° ± 9.3° and 22.9° ± 12.0°, respectively, $P < .05$). For the 10 o'clock position, ITR was similar to the intact knee at 15° of knee flexion (16.7° ± 9.9°, $P > .05$); however it was greater than the intact knee at 30° of knee flexion (22.8° ± 12.6°, $P < .05$). When comparing the 2 femoral tunnel positions, no statistical difference could be shown between them at either flexion angle.

The valgus rotation for the intact knee in response to a combined rotatory load was 5.4° ± 2.5° at 15° of knee flexion and 6.9° ± 3.1° at 30° of knee flexion (Table 3). It should be noted that these values were also more than 5 times the amount of valgus rotation during anterior tibial load, up to 1.1 mm. For both femoral tunnel positions, the valgus rotation was similar to the intact knee at 15° of knee flexion and greater than the intact knee at 30° of knee flexion (8.1° ± 3.8° and 8.0° ± 4.0° for the 11 and 10 o'clock positions, respectively, $P < .05$). When comparing the 2 femoral tunnel positions, no statistical difference could be shown between them at either flexion angle.

The data on the in situ forces in the ACL graft for the 10 o'clock position were found to be close to those for

TABLE 3. *Knee Kinematics in Response to Combined Rotatory Load (Mean ± SD)*

				ACL-Reconstructed Knee	
	Flexion Angle	Intact Knee	ACL-Deficient	11 o'clock	10 o'clock
Anterior tibial translation (mm)	15°	3.6 ± 2.3	10.9 ± 2.8*	4.5 ± 3.2*†	3.5 ± 2.7†‡
	30°	5.7 ± 3.6	12.3 ± 3.9*	7.6 ± 4.1*†	6.9 ± 3.8*†‡
Internal tibial rotation (°)	15°	16.1 ± 8.3	19.6 ± 9.3*	17.3 ± 9.3*†	16.7 ± 9.9†
	30°	20.6 ± 11.1	22.5 ± 11.3*	22.9 ± 12.0*	22.8 ± 12.6*
Valgus rotation (°)	15°	5.4 ± 2.5	7.7 ± 2.6*	5.6 ± 2.5†	5.6 ± 2.6†
	30°	6.9 ± 3.1	10.6 ± 4.2*	8.1 ± 3.8*†	8.0 ± 4.0*†

*$P < .05$ compared with intact knee. †$P < .05$ compared with ACL-deficient knee. ‡$P < .05$ compared with 11 o'clock reconstruction.

TABLE 4. *In Situ Force in Response to Combined Rotatory Load (Mean ± SD N)*

		ACL Graft	
Flexion Angle	Intact ACL	11 o'clock	10 o'clock
15°	83 ± 15	74 ± 24*	80 ± 18
30°	67 ± 12	60 ± 15	70 ± 18†

*$P < .05$ compared with intact ACL.
†$P < .05$ compared with graft placed at 11 o'clock position.

the intact knee and there were no statistically significant differences between them for both 15° and 30° of knee flexion ($P > .05$) (Table 4). On the other hand, the in situ force in the ACL graft for the 11 o'clock position was significantly smaller than that in the intact ACL at 15° of knee flexion (74 ± 24 N *v* 83 ± 15 N, respectively, $P < .05$). In addition, at 30° of knee flexion, the in situ force in the ACL graft at the 11 o'clock position was significantly lower than at the 10 o'clock position (60 ± 15 N *v* 70 ± 18 N, respectively, $P < .05$). However, no statistical difference could be shown between the 11 and 10 o'clock positions at 15° of knee flexion (74 ± 24 N *v* 80 ± 18 N, respectively, $P > .05$).

DISCUSSION

In this study, the biomechanics of the knee following ACL graft replacement by a bone–patellar tendon–bone graft placed at the 11 and 10 o'clock positions were studied and compared. Specifically, the knee kinematics and in situ forces were quantitatively evaluated using the robotic/UFS testing system. The advantages of this testing system include the measurement of kinematics when the knee was unrestricted in its multiple DOF motion as well as simultaneously determining the in situ force in the ACL and ACL graft without attaching mechanical devices to the ligament or the replacement graft. Most importantly, this advanced methodology has advantages of collecting the experimental data from the *same* cadaveric knee specimen under different experimental conditions (such as intact, ACL-deficient, and ACL-reconstructed at 11 and 10 o'clock tunnel positions), thus reducing the effect of interspecimen variation and significantly increasing the statistical power of the data through the use of repeated-measures analysis of variance for data analysis. In other words, even with a large standard deviation, statistical significance can be shown as long as the change in data is consistent between each experimental condition.[24]

The resulting kinematics and in situ forces were similar to those of previously published results.[10,12,13] In comparing the 11 and 10 o'clock positions, the kinematics of the reconstructed knee in response to 134 N of anterior tibial load confirmed our first hypothesis, because both the ATT and in situ forces for the 11 o'clock and 10 o'clock positions were not different from the intact knee at flexion angles below 60°. In terms of in situ force, the results obtained are in agreement with the findings of previous studies.[11] The 10 o'clock position had lower in situ force in the ACL graft at 90° of knee flexion than that of the 11 o'clock position and the magnitude of the forces was relatively lower when compared with those with the knee near extension. It has been shown that the PL bundle (resembling the 10 o'clock position) has higher in situ force at lower knee flexion angles and the AM bundle (resembling the 11 o'clock position) has higher in situ force at higher knee flexion angles.[11] However, the in situ force of the ACL was lower at deep knee flexion angles, indicating that other structures such as the medial collateral ligament and knee contact are contributing to provide knee stability.[25]

In response to a combined rotatory load of 10 N-m valgus and 5 N-m internal tibial torques, the coupled ATT for the 10 o'clock position was smaller than that for the 11 o'clock position at both 15° and 30° of flexion, supporting the second hypothesis. It should be noted that this coupled ATT in response to the combined rotatory load was as large as those in response to the 134 N anterior tibial load, suggesting the ACL does indeed play a key role in stabilizing the knee in response to applied loads from multiple directions. Further, the 11 o'clock position exhibited larger coupled ATT compared with both the intact knee and the 10 o'clock position. The in situ forces for the ACL graft placed at the 11 o'clock position were also significantly lower than those for the intact ACL (at 15° of knee flexion) and at the 10 o'clock position (at 30° of knee flexion). These data suggest the potential advantage of moving the femoral tunnel position away from the center of the knee.[10]

The ITR and valgus rotation of the knee in response to a combined rotatory load were more than 5-fold greater than those under 134 N anterior tibial load. The 11 o'clock position could not restore ITR or valgus rotation at either flexion angle, whereas the 10 o'clock position could restore ITR and valgus rotation to the level of the intact knee at 15° of knee flexion. However, no statistical difference could be shown between the 2 femoral tunnel positions.

The findings of this cadaveric study suggest that placing the femoral tunnel at the 10 o'clock position could improve rotatory knee stability compared with the 11 o'clock position. Both femoral tunnel positions were found to be effective at stabilizing the knee under anterior tibial load. However, when the knee is subjected to combined rotatory loads, the 10 o'clock position is better than the 11 o'clock position; yet neither femoral tunnel position could completely restore the kinematics and the in situ forces to the level of the intact knee. Thus, in isolation, replacing the AM or PL bundle of the ACL alone does not restore the complex function of the intact ACL. Recently, separate cadaveric studies from our research center as well as others, have shown that an anatomic ACL reconstruction replacing both the AM and PL bundles could more closely reproduce knee kinematics and in situ force in the ACL graft to the level of the intact knee.[13,26] Thus, this current study confirms that while the current ACL reconstruction procedures have limitations, moving the femoral tunnel more laterally may have some advantages. These findings support the fact that many surgeons are moving the femoral tunnel position from the 11 or 11:30 o'clock positions to 10 or 10:30 o'clock positions.[15,27,28]

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