Winner of the 2018 Cabaud Award

The Influence of Graft Tensioning Sequence on Tibiofemoral Orientation During Bicruciate and Posterolateral Corner Knee Ligament Reconstruction

A Biomechanical Study

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Background: During multiple knee ligament reconstructions, the graft tensioning order may influence the final tibiofemoral orientation and corresponding knee kinematics. Nonanatomic tibiofemoral orientation may result in residual knee instability, altered joint loading, and an increased propensity for graft failure.

Purpose: To biomechanically evaluate the effect of different graft tensioning sequences on knee tibiofemoral orientation after multiple knee ligament reconstructions in a bicruciate ligament (anterior cruciate ligament [ACL] and posterior cruciate ligament [PCL]) with a posterolateral corner (PLC)–injured knee.

Study Design: Controlled laboratory study.

Methods: Ten nonpaired, fresh-frozen human cadaveric knees were utilized for this study. After reconstruction of both cruciate ligaments and the PLC and proximal graft fixation, each knee was randomly assigned to each of 4 graft tensioning order groups: (1) PCL → ACL → PLC, (2) PCL → PLC → ACL, (3) PLC → ACL → PCL, and (4) ACL → PCL → PLC. Tibiofemoral orientation after graft tensioning was measured and compared with the intact state.

Results: Tensioning the ACL first (tensioning order 4) resulted in posterior displacement of the tibia at 0° by 1.7 ± 1.3 mm compared with the intact state (P = .002). All tensioning orders resulted in significantly increased tibial anterior translation compared with the intact state at higher flexion angles ranging from 2.7 mm to 3.2 mm at 60° and from 3.1 mm to 3.4 mm at 90° for tensioning orders 1 and 2, respectively (all $P < .001$). There was no significant difference in tibiofemoral orientation in the sagittal plane between the tensioning orders at higher flexion angles. All tensioning orders resulted in increased tibial internal rotation (all $P < .001$). Tensioning and fixing the PLC first (tensioning order 3) resulted in the most increases in internal rotation of the tibia: 2.4° ± 1.9°, 2.7° ± 1.8°, and 2.0° ± 2.0° at 0°, 30°, and 60°, respectively.

Conclusion: None of the tensioning orders restored intact knee tibiofemoral orientation. Tensioning the PLC first should be avoided in bicruciate knee ligament reconstruction with concurrent PLC reconstruction because it significantly increased tibial internal rotation. We recommend that the PCL be tensioned first, followed by the ACL, to avoid posterior translation of the tibia in extension where the knee is primarily loaded during most activities. The PLC should be tensioned last.

Clinical Relevance: This study will help guide surgeons in decision making for the graft tensioning order during multiple knee ligament reconstructions.

Keywords: knee ligaments; multiligament injury; tensioning order; knee dislocation; biomechanics of ligament

Knee dislocations are complex injuries that often necessitate multiple concurrent ligament reconstructions to restore native knee stability.[2,8,15,16] When reconstructing multiple knee ligaments concurrently, restoring the native tibiofemoral orientation and associated knee kinematics is challenging but important. The tensioning sequence of the grafts is reported

The American Journal of Sports Medicine
2018;46(8):1863–1869
DOI: 10.1177/0363546517751917

to influence tibiofemoral orientation[27] and graft forces.[19] Thus, an improper tensioning order may contribute to nonanatomic tibiofemoral orientation, leading to overconstraint or residual laxity of the knee joint, altered joint loading, degenerative changes, or graft failure.[2,8,15,16]

The sequence of graft tensioning has been reported to influence joint kinematics.[15,18] In a biomechanical study evaluating graft tensioning order, Markolf et al[19] reported that in the setting of combined anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) reconstruction, tensioning of the PCL first consistently achieved better mean graft forces at 30° of flexion compared with tensioning the ACL first. Markolf et al reported that there was a tendency for the tibia to displace posteriorly when the ACL graft was tensioned first. Wentorf et al[27] evaluated tibiofemoral orientation when tensioning the ACL graft in a posterolateral corner (PLC)–deficient knee and reported that tensioning the ACL graft before the PLC resulted in an externally rotated tibia.

Several graft tensioning sequences have been reported in the literature, but biomechanical validation is lacking.[6,7,18,24] Several authors recommend tensioning and fixation of the cruciate ligaments first, followed by tensioning of the collateral ligaments. Most authors recommend PCL graft tension and fixation first,[4,5,17] while others recommend simultaneous tensioning of the ACL and PCL[18] and fixing the PCL first. However, another group has recommended fixation of the ACL before the PCL.[26] Currently, there is no consensus in the literature with regard to the optimal tensioning order during multiple knee ligament reconstructions. Therefore, the purpose of this study was to biomechanically evaluate the effect of different graft tensioning sequences after bicruciate knee ligament reconstruction involving the PLC (ACL, PCL, and PLC). Our hypothesis was that there would be no difference in tibiofemoral orientation between any of the tensioning orders.

METHODS

Specimen Preparation

Ten nonpaired, fresh-frozen human cadaveric specimens (mean age, 62.3 years [range, 58-65 years]) with no history of injuries, anatomic abnormalities, ligament instability, osteoarthritis, or disease were used for this study. Specimens were stored at –20°C and thawed at room temperature for 24 hours before preparation. The cadaveric specimens utilized in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. All soft tissue structures on the femur and tibia were removed 10 cm proximal and distal to the joint line, respectively. The exposed tibia, fibula, and femur were then fixed in a cylindrical mold with polymethyl methacrylate (Fricke Dental International).

Before the specimen was mounted in the robotic testing system, medial parapatellar arthrotomy was performed, and the menisci, cartilage, and cruciate ligaments were evaluated for any injury. Similarly, in preparation for PLC reconstruction, a lateral hockey stick–shaped incision was made, followed by careful dissection to the iliotibial band.[25] After identification of the relevant structures, sectioning, and surgical procedures, soft tissue and skin incisions were closed before each testing state.

Robotic Testing Setup

Knee biomechanics were assessed with a 6 degrees of freedom robotic testing system (KR 60-3; KUKA Robotics), which has been described and validated previously for knee joint testing.[11,13,22] The potted tibia and fibula were secured to a universal force/torque sensor (Delta F/T Transducer; ATI Industrial Automation) attached at the end effector of the robotic arm via a custom fixture, and the potted femur was securely mounted to a stationary base-plate pedestal (Figure 1).

Before biomechanical testing, a coordinate measuring device (ROMER Absolute Arm; Hexagon Manufacturing Intelligence) was used to record the locations of anatomic landmarks on the femur, tibia, and knee joint. Three-dimensional coordinates representing the medial and lateral epicondyles, medial and lateral joint lines, and the tibial diaphysis were collected.[12,28] The coordinates of the anatomic landmarks were used to define a global coordinate system for the tibia. Before the robotically simulated clinical knee examination, the passive flexion-extension path was determined for each intact knee from full extension to 120° in 1° increments. Forces and torques in the remaining 5 degrees of freedom were minimized, and knee positions were recorded to serve as reference starting points for subsequent testing. A 10-N compressive load was applied coincident to the tibial axis to ensure contact between the femoral condyles and tibial plateau during the acquisition of the passive path and subsequent testing.

ACL Sectioning and Reconstruction

The ACL was sectioned at the midsubstance for the sectioned state. The native ACL's tibial and femoral footprints were

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Presented at the 44th annual meeting of the AOSSM, San Diego, California, USA, July 2018.

One or more of the authors has declared the following potential conflict of interest or source of funding: L.E. has received intellectual property royalties from and is a paid consultant for Arthrex, receives research support from Biomet and Smith & Nephew, and holds stock or stock options in iBalance. R.F.L. is a consultant for Arthrex, Ossur, and Smith & Nephew; receives intellectual property royalties from Arthrex and Smith & Nephew; and receives research support from Arthrex, Ossur, and Smith & Nephew. G.M. receives research support from the Southern and Eastern Norway Regional Health Authority and Arthrex.

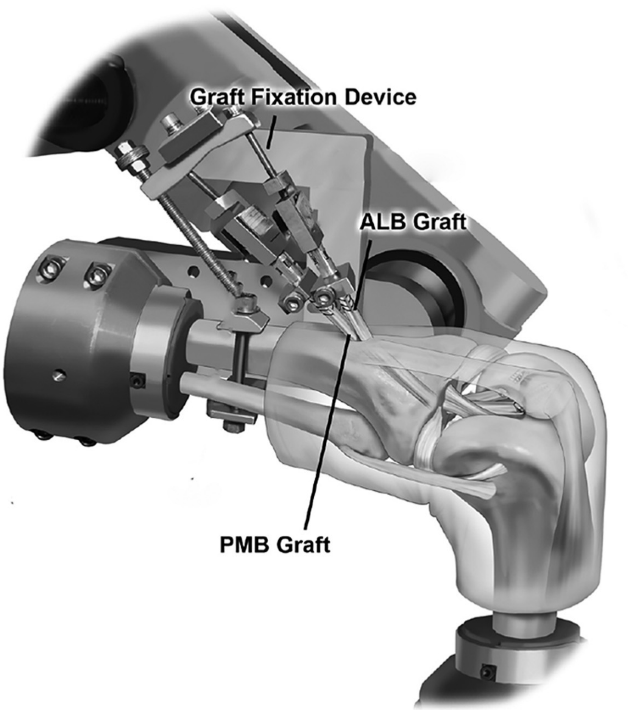

Figure 1. An illustration of the robotic setup for biomechanical testing. All grafts were fixed in a custom-made fixture. In this illustration, only the double-bundle posterior cruciate ligament (PCL) grafts are shown to demonstrate the setup. Showing all the grafts would make it difficult to understand because of the overlap. ALB, anterolateral bundle; PMB, posteromedial bundle.

visually identified through medial parapatellar arthrotomy with the knee flexed to 120° of flexion. With the knee in the robot, anatomic single-bundle ACL reconstruction using a bone–patellar tendon–bone allograft (AlloSource) was performed according to a previously reported technique.[11] The graft was fixed on the femoral side with a 7 × 20–mm cannulated titanium interference screw (Arthrex). Fixation on the tibial side was delayed and performed according to the tensioning sequence protocol. On the tibial side, the ACL graft was fixed on the custom-made fixture with the knee in extension and neutral rotation.

PCL Sectioning and Reconstruction

The PCL was sectioned at both the tibial and femoral attachments. The native PCL's tibial and femoral footprints were visually identified through combined medial parapatellar arthrotomy and a posterior approach (to assess the PCL tibial facet) with the knee flexed to 120° of flexion and at extension, respectively. PCL sectioning and anatomic double-bundle PCL reconstruction were performed with the knee in the robot. The centers of the anterolateral and posteromedial bundles (ALB and PMB, respectively) were identified using the anatomic landmarks previously described by Anderson et al,[1] and double-bundle PCL reconstruction using an 11-mm Achilles tendon allograft for the ALB and a 7-mm tibialis anterior allograft for the PMB as previously described was performed.[13,23] The ALB graft was fixed on the femur with a 7 × 20–mm cannulated titanium interference screw (Arthrex), and the PMB graft was fixed with a 7 × 23–mm cannulated bioabsorbable screw (Arthrex). Both grafts were passed distally through the tibial tunnel. Femoral fixation was carried out, and fixation on the tibial side was delayed until randomization of the tensioning order protocol.

PLC Sectioning and Reconstruction

The static stabilizers of the PLC, fibular collateral ligament (FCL), popliteofibular ligament (PFL), and popliteus tendon, were identified and isolated through a lateral hockey stick–shaped incision. Next, the structures were sectioned, simulating a grade 3 posterolateral injury. PLC reconstruction was performed with the knee in the robot using the technique described by LaPrade et al.[14] Femoral fixation was carried out, while fixation to the fibula and tibia was delayed until the randomization of fixation order according to the study protocol. Each of the 2 grafts was fixed on the femur with a 7 × 20–mm cannulated titanium interference screw (Arthrex). The FCL graft was fixed in its fibular tunnel with a cannulated bioabsorbable interference screw with the knee at 30° of flexion, neutral rotation, and slight valgus stress applied to reduce any potential varus opening of the lateral compartment of the knee. The screw fixing the FCL graft in the fibular head was upsized after each test to ensure good graft fixation. The popliteus tendon and PFL grafts were then fixed at 60° of knee flexion and with the knee in neutral rotation. A custom tensioning fixture was utilized for fixation of all the grafts on the tibial side (Figure 1). Before testing, the fixture was validated to demonstrate rigid graft fixation (ie, no slippage).

Biomechanical Testing

After reconstruction of the cruciate ligaments and PLC, each knee underwent 4 different graft tensioning orders, and kinematic testing was performed after each order. Kinematic testing consisted of bringing the knee to 0°, 30°, 60°, and 90° of flexion and minimizing the forces and torques to assess the new neutral tibiofemoral orientation after reconstruction. The neutral tibiofemoral orientation for each tensioning order was recorded and compared with that of the intact knee to measure the effect of reconstruction on passive knee kinematics. The sequence of tensioning orders was randomized. The 4 graft tensioning orders used were (1) PCL → ACL → PLC, (2) PCL → PLC → ACL, (3) PLC → ACL → PCL, and (4) ACL → PCL → PLC (Table 1). Each knee underwent 1 cycle of kinematic testing using a randomly chosen tensioning order (tensioning order 2) to precondition the grafts before the actual test. Pilot testing demonstrated that the grafts did not significantly elongate after preconditioning. In each knee, tibiofemoral orientation using the predefined landmarks was recorded and compared with the intact state.

TABLE 1
Graft Tensioning Order[a]

Group	Tension 1	Tension 2	Tension 3
1	PCL	ACL	PLC
2	PCL	PLC	ACL
3	PLC	ACL	PCL
4	ACL	PCL	PLC

[a]Each knee was subjected to each of the tensioning orders, and the orders were randomized for each knee. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner.

During pilot testing, keeping the knee secured at both ends in the robot was found to be too rigid to allow for the movement during tensioning that is observed in the clinic; therefore, tensioning was performed with the femur free from the pedestal while the tibia remained clamped in the end effector. After tensioning all the grafts, the femur was resecured in the pedestal in the same position. To ensure positional accuracy when remounting, the robotic arm was returned to the previously recorded dismounting location (0° of flexion, neutral rotation). Additionally, relative internal/external rotation of the femur was prevented using set screws, as shown in Figure 1. The other degrees of freedom were constrained by the clamp itself. This method of dismounting and remounting was validated for repeatability by repeating the kinematic testing cycle 9 times without dismounting and then 10 times dismounting and remounting between each test on an intact pilot specimen. The results of this validation can be found in the Appendix (available in the online version of this article). Furthermore, reduction of the tibiofemoral joint and controlling internal rotation during graft tensioning were found to be important. Testing commenced only after repeatability and consistency were attained in the setup and testing.

Statistical Analysis

All measurement variables were normally distributed, so parametric statistical tools were used to make all comparisons among knee conditions. The primary aims of this study were to compare the effect of different graft tensioning sequences after multiple knee ligament reconstructions involving the PLC (ACL, PCL, and PLC) on tibiofemoral orientation relative to the intact state and in comparison to the other tensioning sequences. To address these goals, 1-factor linear mixed-effects models were constructed to compare conditions at each tested flexion angle. Random intercepts were allowed for each specimen to match the repeated-measures design of the study. Tukey post hoc comparisons were performed. The covariance structure for these models was chosen using the Bayesian information criterion, and confirmation of model assumptions and fit were assessed via residual diagnostics. Additionally, paired t tests were used to compare each tensioning sequence to the intact state. A power calculation was performed using a simplification of the ultimate analysis methods. Assuming 2-tailed matched-pairs t testing and alpha of 0.05, 10 knees was sufficient to detect an effect size of $d = 1$ with 80% statistical power. The statistical software R was used for all analyses (R Foundation for Statistical Computing with ggplot2, nlme, and multcomp).

RESULTS

Anterior and Posterior Translation

None of the tensioning orders restored tibiofemoral orientation to the intact state in anterior-posterior translation. Most tensioning orders were significantly different from the intact state at all angles except tensioning orders 1 (PCL → ACL → PLC), 2 (PCL → PLC → ACL), and 3 (PLC → ACL → PCL) at 0° and tensioning orders 1 and 4 (ACL → PCL → PLC) at 30°. Tensioning the ACL first (tensioning order 4) resulted in posterior displacement of the tibia by 1.7 ± 1.3 mm compared with the intact state at 0° ($P = .002$). When tensioning the PCL first (tensioning orders 1 and 2), tibial translation was not significantly different from the intact state at 0° and 30° except when the PLC was tensioned before the ACL at 30°. All tensioning orders were significantly different from the intact state at 60° and 90° (Table 2 and Figure 2).

Internal and External Rotation

All tensioning sequences resulted in significantly increased tibial internal rotation after tensioning and fixing the grafts compared with the intact state with the exception of tensioning orders 1 and 4 at 90° of flexion. Tensioning and fixing the PLC first (tensioning order 3) resulted in the most internal rotation of the tibia: 2.4° ± 1.9°, 2.7° ± 1.8°, and 2.0° ± 2.0° at 0°, 30°, and 60°, respectively (Table 3 and Figure 3). Pairwise comparisons did not demonstrate significant differences between the tensioning orders.

DISCUSSION

The most important finding of this study was that the tensioning order of grafts with bicruciate ligament and concurrent PLC reconstruction affected tibiofemoral orientation. None of the tensioning orders tested restored the knee back to the intact tibiofemoral orientation. Tensioning the PLC first resulted in an internally rotated tibia at lower flexion angles and should therefore be avoided. Tensioning the ACL first increased the risk of tibial posterior translation in extension where the knee is primarily loaded during most activities; therefore, we recommend that the PCL be tensioned first.

All tensioning orders resulted in a significant increase in anterior translation of the tibia at higher flexion angles compared with the intact state; however, there was no significant difference in tibial displacement between tensioning order 1 (PCL → ACL → PLC) and tensioning order 4 (ACL → PCL → PLC) at 60°. Most authors advocate for

TABLE 2
Pairwise Comparison of Tibial Anterior and Posterior Displacement Between the Tensioning Orders at Different Angles for the Zero-Force State[a]

Flexion Angle	Tensioning Order 2 vs 1	Tensioning Order 3 vs 1	Tensioning Order 4 vs 1	Tensioning Order 3 vs 2	Tensioning Order 4 vs 2	Tensioning Order 4 vs 3
0°	0.6 ± 0.2[b]	0.0 ± 0.3	–1.2 ± 0.3[b]	–0.6 ± 0.2[b]	–1.7 ± 0.2[b]	–1.1 ± 0.1[b]
30°	0.7 ± 0.2[b]	0.2 ± 0.4	–1.0 ± 0.3[b]	–0.5 ± 0.2	–1.7 ± 0.2[b]	–1.3 ± 0.2[b]
60°	0.5 ± 0.2	0.1 ± 0.5	–0.8 ± 0.3	–0.4 ± 0.3	–1.3 ± 0.2[b]	–0.9 ± 0.2[b]
90°	0.3 ± 0.2	0.0 ± 0.4	–0.7 ± 0.3[b]	–0.3 ± 0.2	–1.0 ± 0.2[b]	–0.7 ± 0.2[b]

[a]Data are reported as mean ± standard error (in mm). Standard errors derived from linear mixed-effects model. Tensioning order 1: PCL → ACL → PLC; tensioning order 2: PCL → PLC → ACL; tensioning order 3: PLC → ACL → PCL; and tensioning order 4: ACL → PCL → PLC. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner.
[b]Significant difference for that comparison.

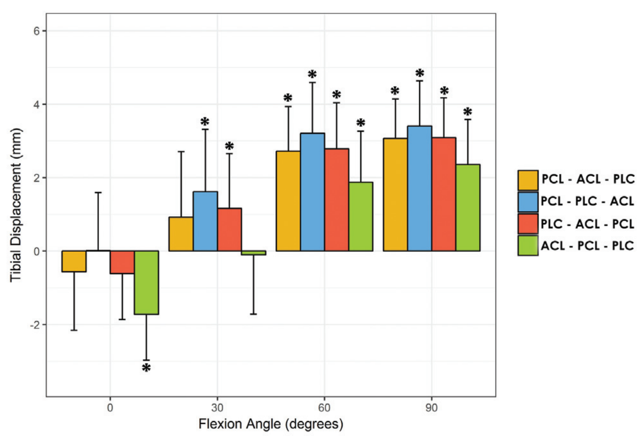

Figure 2. Mean changes from the intact state in tibial anterior-posterior displacement after different tensioning sequences (error bars represent ±1 SD). The magnitude demonstrates changes after each tensioning sequence with the intact state subtracted. Positive values denote anterior translation, and negative values denote posterior translation of the tibia. Tensioning order 1: PCL → ACL → PLC; tensioning order 2: PCL → PLC → ACL; tensioning order 3: PLC → ACL → PCL; and tensioning order 4: ACL → PCL → PLC. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner. *Significantly different from the intact native state ($P < .05$).

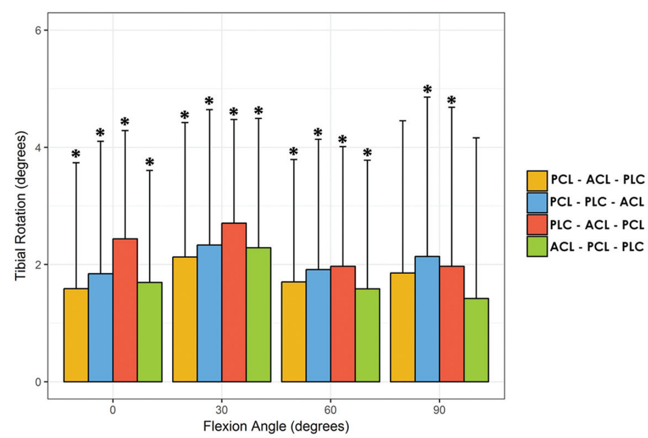

Figure 3. Mean changes from the intact state in tibial internal rotation (error bars represent ±1 SD) in response to the different tensioning orders. For tensioning orders 1, 2, and 4, at all flexion angles except at 30°, the resultant internal rotation after tensioning was <2°. Tensioning order 3 produced more internal rotation of the tibia at lower flexion angles. Positive values denote that the tibia was internally rotated. Tensioning order 1: PCL → ACL → PLC; tensioning order 2: PCL → PLC → ACL; tensioning order 3: PLC → ACL → PCL; and tensioning order 4: ACL → PCL → PLC. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner. *Significantly different from the intact native state ($P < .05$).

fixing the PCL first to restore the tibial step-off and avoid fixing the tibia in a posterior subluxation position.[3,4,9,16,20,21] However, there is little discussion in the literature on the risk of displacing the tibia too anteriorly in an ACL-deficient knee when tensioning a PCL graft. The effect of anterior translation of the tibia at higher flexion angles in all tensioning sequences is difficult to determine. Surgeons should be aware of the risk of tibial anterior translation at higher flexion angles and avoid overcorrection of the tibial step-off. When the ALB of the PCL is fixed at 90°, care must be taken to compare the tibial step-off to the uninjured side (both extremities can be prepared and draped), or the use of an intraoperative radiograph should be considered to control the tibial step-off.

Tensioning and fixing the ACL graft before the PCL graft resulted in significantly increased posterior translation of the tibia in extension where the ACL graft was fixed. At 0° and 30°, tibial translation was within 1 mm of the intact state for tensioning order 1. Markolf et al[19] reported increased tibial posterior displacement and increased graft forces when the ACL was tensioned before the PCL. During normal gait, most of the stance phase occurs at <20° of knee flexion, and most knee joint loading occurs at lower knee flexion angles. The total force transmitted through the knee joint during level walking is 2 to 4 times the body weight. If the tibia is posteriorly translated at lower flexion angles, as was observed when the ACL was tensioned first, it may lead to altered joint forces,

TABLE 3
Pairwise Comparison of Tibial Internal and External Rotation Between the Tensioning Orders at Different Angles for the Zero-Force State[a]

Flexion Angle	Tensioning Order 2 vs 1	Tensioning Order 3 vs 1	Tensioning Order 4 vs 1	Tensioning Order 3 vs 2	Tensioning Order 4 vs 2	Tensioning Order 4 vs 3
0°	0.3 ± 0.2	0.9 ± 0.6	0.1 ± 0.3	0.6 ± 0.4	–0.1 ± 0.3	–0.7 ± 0.4
30°	0.2 ± 0.2	0.6 ± 0.5	0.2 ± 0.4	0.4 ± 0.3	0.0 ± 0.3	–0.4 ± 0.3
60°	0.2 ± 0.3	0.3 ± 0.4	–0.1 ± 0.3	0.1 ± 0.2	–0.3 ± 0.2	–0.4 ± 0.2
90°	0.3 ± 0.3	0.1 ± 0.4	–0.4 ± 0.3	–0.2 ± 0.2	–0.7 ± 0.3[b]	–0.5 ± 0.3

[a]Data are reported as mean ± standard error (in deg). Standard errors derived from linear mixed-effects model. Tensioning order 1: PCL → ACL → PLC; tensioning order 2: PCL → PLC → ACL; tensioning order 3: PLC → ACL → PCL; and tensioning order 4: ACL → PCL → PLC. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner.
[b]Significant difference for that comparison.

which can potentially accelerate degenerative joint changes. Furthermore, posterior translation of the tibia during loading may expose the PCL to excessive forces, ultimately leading to graft failure. Because of these reasons, our recommendation is to avoid tensioning the ACL first.

The tensioning order also affected rotational tibiofemoral orientation. Tensioning the PLC first (tensioning order 3) resulted in more increased internal rotation of the tibia compared with the intact state at lower flexion angles. Tensioning either the PCL or ACL first (tensioning orders 1, 2, and 4) produced internal rotation of the tibia that was $<2°$ except at 30 degrees of flexion (2.1° for order 1; 2.3° for order 2; 2.3° for order 3) and 90° of flexion (2.1° for order 2), and this may not be clinically significant. Currently, there are no data in the literature on how much rotation is clinically significant. Tensioning the PLC first internally rotated the knee significantly, and this can pose a problem when performed in staged procedures where the PLC is reconstructed early and the cruciate ligaments at a later stage. By internally rotating the tibia during PLC reconstruction and graft fixation, tibiofemoral loading and graft forces could be altered. Wentorf et al[27] reported increased tibial external rotation when the ACL was fixed in PLC-deficient knees, prompting some authors to fix the PLC before the ACL to avoid increases in external rotation. In the present study, there was no significant difference in internal rotation of the tibia between tensioning the PLC before the ACL and tensioning the ACL before the PLC.

We acknowledge some limitations to this study. Not all possible tensioning orders could be tested. The application of multiple loading conditions at each flexion angle may result in laxity of the surrounding soft tissue structures. However, this effect was limited by randomizing the order of graft fixation angles and knee flexion angles during testing. In addition, we limited the effect of dependent variables by using the same graft fixation materials and commercially prepared allografts for every reconstruction procedure. Also, consistency was maintained between manufacturer and reamer type during the surgical protocol to minimize aperture variability and tunnel dimensions.[10] Finally, several pilot tests were performed to establish reproducible and highly accurate testing procedures using a 6 degrees of freedom robotic system. In addition, none of the tested tensioning orders restored tibiofemoral orientation to that of the intact state.

CONCLUSION

None of the tensioning orders restored intact knee tibiofemoral orientation in this cadaveric model. Tensioning the PLC first should be avoided in bicruciate knee ligament reconstruction with concurrent PLC reconstruction because it significantly increased tibial internal rotation. We recommend that the PCL be tensioned first, followed by the ACL, to avoid posterior translation of the tibia in extension where the knee is primarily loaded during most activities. The PLC should be tensioned last.

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