

Effect of Sectioning of the Anterior Cruciate Ligament and Posterolateral Structures on Lateral Compartment Gapping

A Randomized Biomechanical Study

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Background: The contribution of anterior cruciate ligament (ACL) injury to lateral instability under varus stress, particularly compared with posterolateral structures, is not well known.

Purpose: To investigate the effect of sectioning the ACL and posterolateral knee structures on lateral compartment gapping under varus stress.

Study Design: Controlled laboratory study.

Methods: Fourteen nonpaired cadaveric knees were randomized to 1 of 2 groups: sequential sectioning of the ACL, fibular collateral ligament (FCL), popliteus tendon (PLT), and popliteofibular ligament (PFL) (ACL-first group) or sequential sectioning of the FCL, PLT, PFL, and ACL (FCL-first group). Knees were loaded onto a custom jig at a 20° flexion angle. A standardized 12-N·m varus moment was applied to each specimen in the intact state and after each randomized sequential-sectioning state. Lateral compartment opening was measured on radiographs to assess the contribution to the increase in the lateral gap caused by resecting the respective structure. The distance was measured by 3 observers on 15 images (5 testing states each imaged 3 times) per specimen, for a total of 210 radiographs. The articular cartilage surfaces were not included in the measurements.

Results: The mean increase in lateral opening after sectioning all structures (ACL and posterolateral corner) was 4.6 ± 1.8 mm (range, 1.9-7.7 mm). The ACL and FCL sectioning contributed the most to lateral knee opening (1.3 ± 0.6 and 2.2 ± 1.3 mm, respectively). In both groups, lateral gapping >3 mm was achieved only after both the ACL and FCL were sectioned. All comparisons of increased mean gapping distances demonstrated a significant difference with subsequent sequential sectioning of structures, except comparisons between the FCL and PLT and the PLT and PFL. When considering the effect of the ACL on lateral opening, no significant difference was found between sectioning the ACL first or FCL first ($P = .387$).

Conclusion: ACL deficiency significantly increased lateral opening under varus stress, regardless of the sequence of injury. The effect of injury to the ACL in addition to the lateral structures should be considered when using varus stress radiographs to evaluate knee injuries.

Clinical Relevance: With the current findings, understanding the effect of ACL and posterolateral corner injuries on lateral gapping under varus stress can aid in correctly diagnosing knee injuries and determining appropriate treatment plans.

Keywords: anterior cruciate ligament; knee; varus stress; biomechanics

The anterior cruciate ligament (ACL) acts as the primary restraint to anterior translation of the tibia while preventing internal and external rotation of the tibia relative to the femur.^{14,23} Experimental studies have examined the

biomechanical role of the ACL in the coronal plane and the interaction between the ACL and the medial collateral ligament with regard to valgus stress.^{3,7,18,21,24} As such, the ACL has been reported to have an important role in valgus instability.^{1,7,19} Biomechanical investigations regarding the relationship between the ACL and lateral structures of the knee have reported an increased force on the ACL with varus loading after sectioning of the posterolateral

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structures.^{16,17,20} However, the data in the literature on the contribution of ACL injury to lateral instability under varus stress, particularly compared with injury of the posterolateral structures, are not as sufficient as the data on the effect of this injury on valgus instability.

It is important to understand the effect of an ACL injury on lateral gapping under varus stress to accurately diagnose knee injuries and determine appropriate treatment plans. In 1981, Grood et al³ demonstrated that the cruciate ligaments together contributed to 22.2% and 12.3% of the total restraining moment against varus load at 5° and 25° of flexion, respectively. Furthermore, the effect of ACL deficiency on varus stress on lateral compartment opening has been reported in 2 recent studies conducted with a similar experimental design but following different sectioning sequences.^{15,20} LaPrade et al¹⁵ reported on a fibular collateral ligament (FCL)—first sectioning method. This allowed the authors to assess the influence of the ACL on lateral gapping under varus stress in a secondary role. Those authors reported a significant increase in lateral opening caused by ACL sectioning. Conversely, McDonald et al²⁰ sectioned the ACL first, followed by the FCL, to investigate the primary role of the ACL in lateral opening, finding no significant increase in lateral opening caused by ACL sectioning when testing at 12 N·m.

The purpose of this study was to investigate the effect of sectioning the ACL and lateral knee structures on lateral compartment gapping under varus stress, randomized into 2 sectioning groups. The null hypothesis was that ACL sectioning would not affect lateral opening under varus stress, regardless of the sectioning order.

METHODS

Specimen Preparation

The cadaveric specimens used in this study were donated from a tissue bank for the purpose of medical research and subsequently purchased by our institution. Because of the use of deidentified cadaveric specimens, this study was exempt from institutional review board approval at our institution. Fourteen nonpaired, fresh-frozen cadaveric knees (distal femur and proximal tibia) without gross evidence of ligamentous injury on clinical examination and evidence of osteoarthritis on radiographic examination were used in this study. Similar to previous studies,^{15,20} nonpaired specimens were chosen over paired specimens because of the lack of significant side-to-side variability

between paired knees.^{10,29} There were 10 male and 4 female donors used in this study with an average age of 49.7 ± 5.0 years (range, 35–54 years).

Each specimen was randomized to 1 of 2 groups: sequential sectioning of the ACL, FCL, popliteus tendon (PLT), and popliteofibular ligament (PFL) (ACL-first group) or sequential sectioning of the FCL, PLT, PFL, and ACL (FCL-first group). Stratified randomization was used to avoid an imbalanced allocation of samples.

The specimens were kept frozen at –20°C before thawing at room temperature for 2 days before potting and testing. Soft tissues were completely dissected from the proximal femur to allow for potting of the specimen in polyvinyl chloride pipes using plaster of Paris. Potting of the specimens in anatomic position was performed 15 cm from the joint line on the femur. Skin and subcutaneous fat on the lateral aspect of the knee joint were further removed to aid in structure access and identification, leaving the fascia intact. The FCL, PLT, and PFL were accessed using a fascial-splitting posterolateral approach,²⁵ and the ACL was accessed using a mini-arthrotomy medial parapatellar approach. Each structure was tagged using suture upon identification.

Biomechanical Testing

Specimens were loaded onto a custom jig with the potted femur rigidly secured and the distal tibia held on a plate that could accommodate knee flexion angles from 0° to 90°. The flexion angle of 20° was chosen in accordance with International Knee Documentation Committee reporting guidelines for lateral compartment opening.⁹ A threaded hook was secured bicortically in the tibial diaphysis 10 cm distal to the joint line and directed medially and perpendicular to the tibial shaft. A standardized 12-N·m varus moment was applied via an S-type Load Cell (Interface) using the threaded bicortical screw and string (Figure 1). A 12-N·m varus moment was selected based on the methodology of previous studies.^{15,20} Tibial rotation and knee flexion during application of the varus moment were prevented by placing a platform parallel to the ground under the distal end of the tibia, which was allowed to glide freely along the jig in only the valgus and varus directions. Each specimen was tested in 5 states: intact and after sequential sectioning of the ACL, FCL, PLT, and PFL, in the described orders.

Images were obtained using a portable C-arm fluoroscopy unit (OEC 9900 Elite Mobile C-arm; GE Healthcare),

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Ethical approval was not sought for the present study.

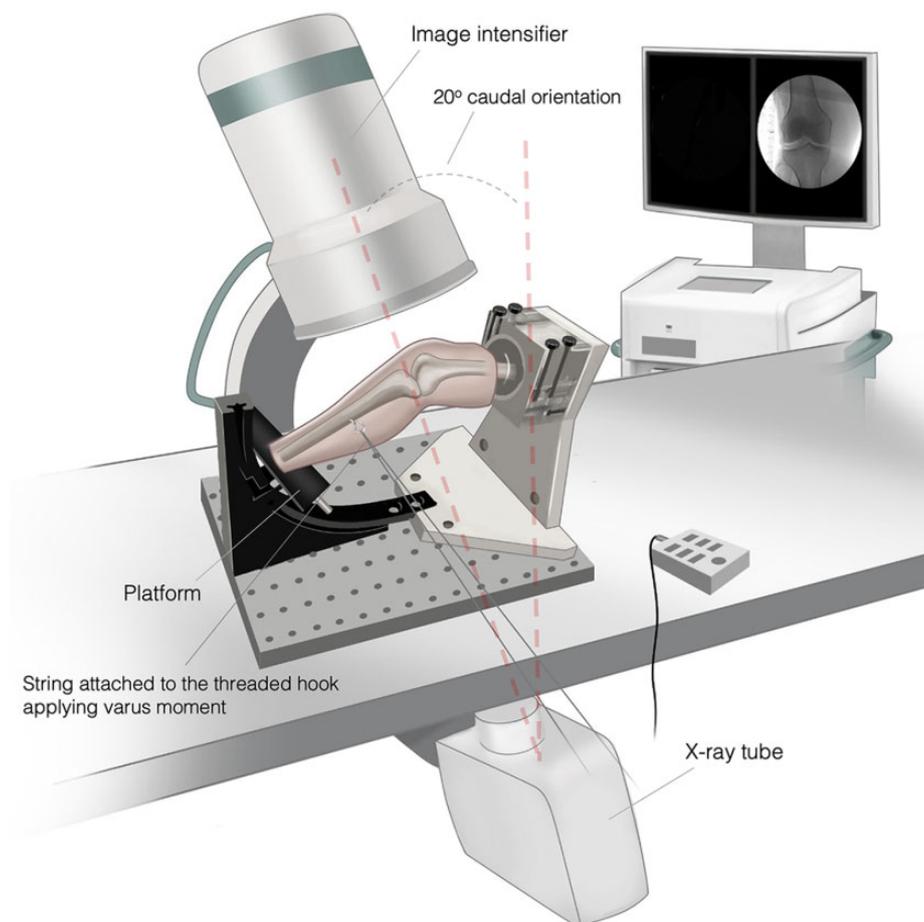


Figure 1. Illustration demonstrating a medial view of the varus stress testing setup in a right knee flexed to 20° on the radiolucent custom jig.

with the image intensifier positioned anterior to the knee. The C-arm was angled 20° caudal to obtain images parallel to the joint line (Figure 1). A radiopaque ruler was placed at the level of the joint and in alignment with the anatomical axis of the distal femur in the sagittal plane. The ruler was positioned 20 cm below the image intensifier of the fluoroscopy unit, allowing for magnification correction. Calibration of the ruler measurement was preserved in the experimental setup because the distance between the joint and the image intensifier in the sagittal plane was held constant in all specimens. All 5 testing states were imaged 3 times using the fluoroscopic C-arm, resulting in 15 images per specimen (210 images overall).

Data Analysis

Images from the fluoroscopic C-arm were saved to the institution's picture archiving and communication system (PACS). The distance between the lateral femoral condyle and the equivalent lateral tibial plateau was measured by extending a vertical line from the most inferior aspect of the lateral femoral condyle to the corresponding point on the lateral tibial plateau using the PACS system in pixels and

converted to millimeters via reference measurement of the distance between the centerlines denoting 1 cm of the radiopaque ruler (Figure 2). The articular cartilage surfaces were not included in the measurements.

Intraobserver Repeatability and Interobserver Reproducibility

Measurements were obtained on the 210 radiographs by 3 individuals, all of whom were blinded to the others' measurements. The radiographs were directly read off of the PACS file and were not reordered between observer readings. Interobserver reproducibility was determined by having 3 different examiners with different levels of training, including a medical student (N.D.; observer 1), an orthopaedic sports medicine research fellow (S.G.; observer 2), and an orthopaedic sports medicine faculty member (J.C.; observer 3), independently measure the varus stress radiographs of each knee.

Statistical Analysis

Intraobserver and interobserver reproducibility of the measurements were evaluated by comparing the means of



Figure 2. Fluoroscopic images of a left knee with arrow demonstrating measurement of lateral opening under a 12-N-m varus load in the (A) intact, (B) anterior cruciate ligament–sectioned, and (C) fibular collateral ligament–sectioned states.

lateral compartment gapping and by calculating intraclass correlation coefficients (ICCs). Distributions were analyzed for a comparison of continuous measurements between the groups, wherein the Mann-Whitney *U* test was used for variables with a nonparametric distribution. The Wilcoxon signed-rank test was used to compare the differences in gap opening of the structures with respect to the other sectioned states, respectively. Bonferroni correction was applied while evaluating the comparison results of the differences in 5 states ($P = .05$ divided by 5). The statistical significance level was considered as .05 in all other tests. In order to identify whether there was a significant difference in lateral gapping under varus stress based on sectioning order (ACL-first and FCL-first), we conducted an a priori power analysis and determined that 14 specimens total (7 per group) were necessary to identify a difference between the 2 groups, with a power of 0.95 and an alpha of 0.05 when utilizing the gapping measures established by McDonald et al²⁰ (ACL-first: 0.31 ± 0.15) and LaPrade et al¹⁵ (FCL-first: 1.91 ± 0.95 [standard deviation estimated assuming a coefficient of variation of 0.05, as no measures of dispersion were provided by either referenced study]). All statistical analyses were performed using SPSS 25.0 software (IBM Corp).

RESULTS

There were no significant differences in age and sex between the specimens' randomized sectioning groups. In both groups, all comparisons of increased mean gapping distances demonstrated a significant difference with subsequent sequential sectioning of structures, with the exception of comparisons between the FCL and PLT and the PLT and PFL sectioning states (Table 1). In the ACL-first group, isolated ACL and FCL sectioning contributed 1.1 ± 0.5 mm and 2.5 ± 1.4 mm, respectively, and in the FCL-first group, isolated FCL and ACL sectioning contributed 1.9 ± 1.3 mm and 1.4 ± 0.7 mm, respectively. In both groups, lateral gapping of >3 mm was achieved only after both the ACL and FCL were sectioned. There was no significant difference

TABLE 1
Comparison of Lateral Compartment Gapping Between Intact and Sectioned States and Subsequent Total Gapping Amount After Adding Each Sectioned State Under a 12-N-m Varus Load^a

	Lateral Gapping, mm	
	Isolated Effect (<i>P</i> Value vs Intact)	Total Gapping After Sectioned State
ACL-first group		
ACL	1.14 (<.0001)	1.14
FCL	2.48 (<.0001)	3.62
PLT	0.77 (.267)	4.39
PFL	0.54 (.296)	4.93
FCL-first group		
FCL	1.9 (<.0001)	1.9
PLT	0.63 (.042)	2.53
PFL	0.3 (.352)	2.83
ACL	1.44 (<.0001)	4.27

^aData are presented as means. ACL, anterior cruciate ligament; FCL, fibular collateral ligament; PFL, popliteofibular ligament; PLT, popliteus tendon.

between the groups in terms of the total amount of lateral gapping obtained after sectioning of all structures ($P = .211$) (Figure 3).

The effects of each sectioning state on lateral opening under varus load in both groups were compared to reveal the effect of the sectioning sequence. There was no significant difference in the amount of lateral opening caused by the sectioning of each state between the 2 groups (Figure 4). When considering the effect of the ACL on lateral opening, no significant difference was found between sectioning the ACL first and the FCL first ($P = .387$).

The means of sectioning states in both groups were calculated, and the effects on lateral opening were compared. The mean increase in lateral opening after sectioning all states was 4.6 ± 1.8 mm (range, 1.94-7.68 mm). Sectioning of the

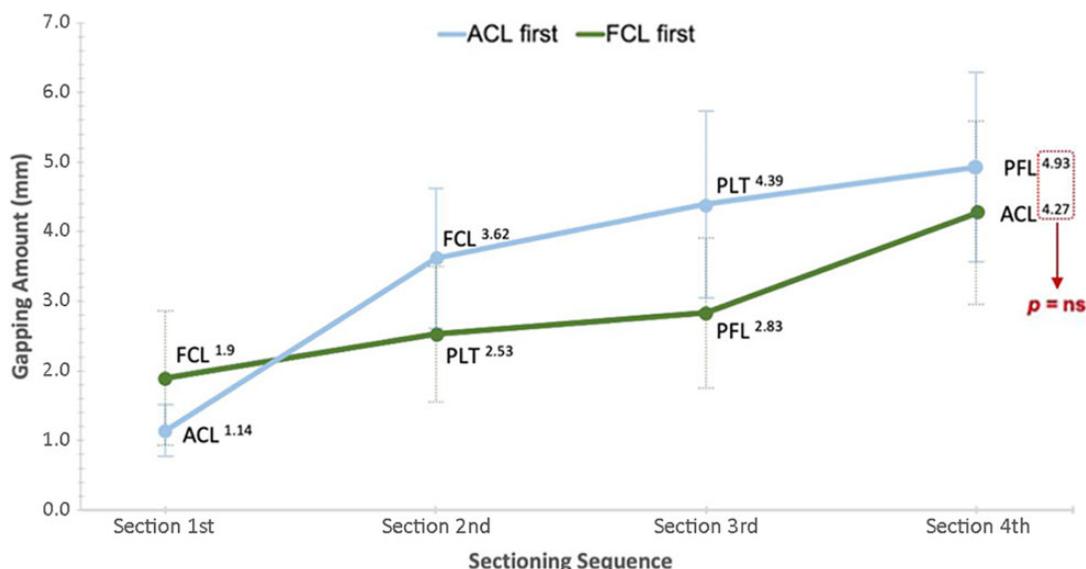


Figure 3. Line graph showing the contribution of each sequentially sectioned structure in addition to intact state in each group. There was no significant difference between the groups in terms of the total amount of lateral gapping obtained after sectioning of all structures. ACL, anterior cruciate ligament; FCL, fibular collateral ligament; ns, nonsignificant; PFL, popliteofibular ligament; PLT, popliteus tendon.

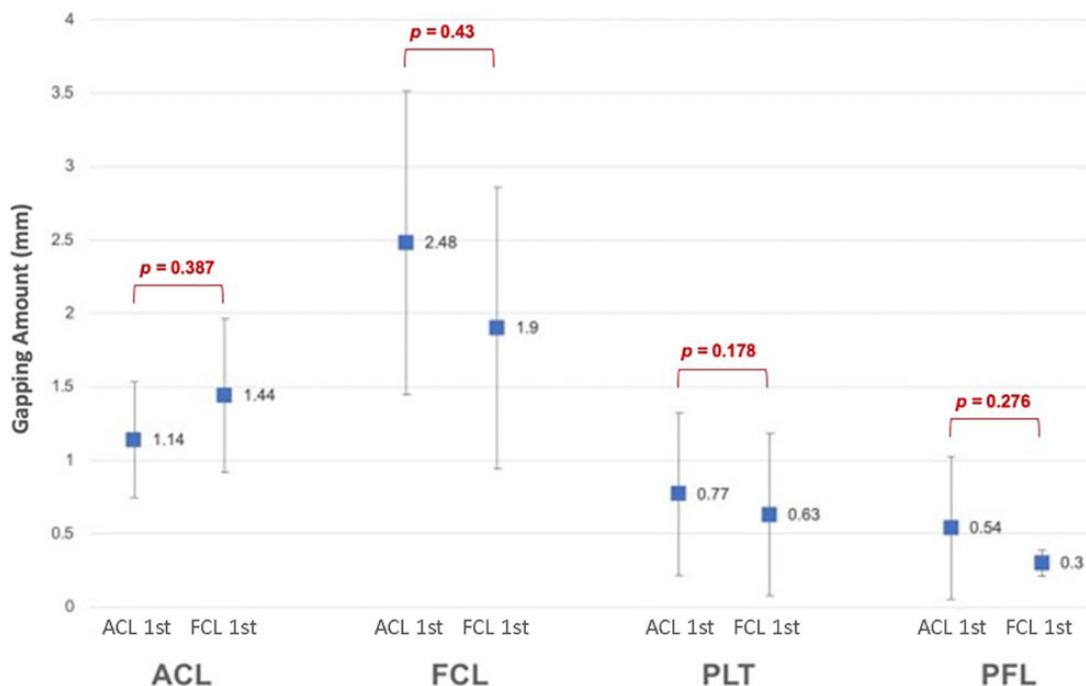


Figure 4. Comparisons of the lateral compartment gapping contributed by each sectioned state in each group under a 12-N-m varus load. The mean increase in lateral gapping in millimeters is presented with the 95% CI after each sectioning state. There was no significant difference in the amount of lateral opening caused by the sectioning of each structure between the 2 groups. ACL, anterior cruciate ligament; FCL, fibular collateral ligament; PFL, popliteofibular ligament; PLT, popliteus tendon.

ACL contributed to 1.3 ± 0.6 mm (95% CI, 0.96-1.61 mm) of lateral opening, while sectioning of the FCL contributed to 2.2 ± 1.3 mm (95% CI, 1.50-2.89) of lateral opening. Sectioning of the FCL and the ACL demonstrated the largest amount

of lateral opening compared with the other sectioned structures. There was no significant difference between the ACL and FCL and between the PLT and PFL in terms of lateral opening length in millimeters (Figure 5).

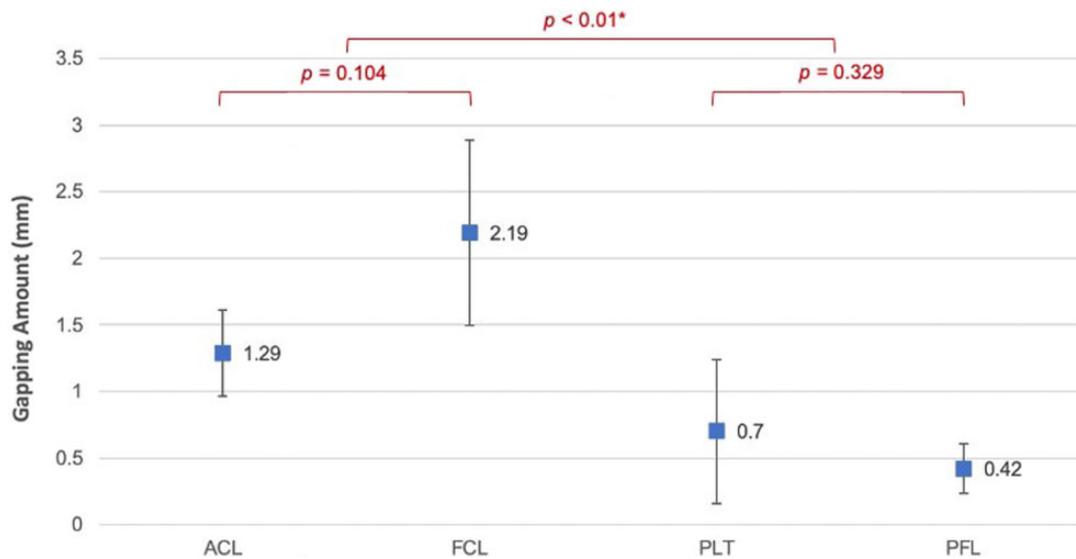


Figure 5. Overall lateral gapping amounts created by each sectioned state and comparison between each state. The mean increase in lateral gapping with the 95% CI after each sectioning state is represented. *Statistically significant difference ($P < .05$). ACL, anterior cruciate ligament; FCL, fibular collateral ligament; PFL, popliteofibular ligament; PLT, popliteus tendon.

The intraobserver ICCs for each of the individual observers were all 0.94 (95% CI, 0.86-0.98), and the interobserver ICCs for trial 1, trial 2, trial 3, and the combined trials' data sets were all 0.95. Both intra- and interobserver ICCs indicated excellent reliability.

DISCUSSION

The most important findings of this study were that ACL sectioning and FCL sectioning produced 1.3 mm and 2.2 mm of comparative lateral opening, respectively. In both groups, a lateral gapping of >3 mm represented a combined ACL- and FCL-sectioned state. When all posterolateral corner structures and the ACL were sectioned, a lateral gapping >4.2 mm was observed. When considering the effect of the ACL on lateral opening, no significant difference was found between sectioning the ACL first and the FCL first.

Assessing the ACL in a secondary role, LaPrade et al¹⁵ separately applied a standardized 12-N·m varus force and clinician-applied varus stress, reporting that the ACL injury provides a further increase of 1.91 mm of the total average 5.26-mm lateral opening increase caused by FCL, PLT, PFL, and ACL sectioning under an applied varus load. McDonald et al²⁰ hypothesized that ACL injury would create a false impression of lateral injury in investigating the primary role of the ACL. They reported that the ACL injury provided 0.31 mm of the average 1.94-mm lateral opening caused by the ACL, FCL, PLT, and PFL incision under a 12-N·m varus moment. By determining that the FCL caused a 1.17-mm opening under the same load, the authors concluded that an isolated ACL deficiency would not contribute to lateral opening to the degree of falsely indicating a lateral injury. Although following 2 different sectioning

orders, there are incremental differences between these 2 studies in terms of proportional and absolute gapping distance regarding the primary and secondary effect of the ACL injury on lateral opening under varus load. As a contribution to these studies, the current study has been carried out with the hypothesis that the effect of the ACL on varus stability can be demonstrated via the randomization of specimens into 2 sectioning sequences. The results of this study showed that sectioning of the ACL constitutes 1.29 ± 0.6 mm of lateral opening after sectioning of the ACL, FCL, PLT, and PFL.

In the current study, sectioning of the ACL contributed to 1.1 ± 0.5 mm of lateral opening in the ACL-first group and 1.4 ± 0.7 mm in the FCL-first group. Grood et al⁴ reported that sectioning of the PCL does not contribute to varus instability when the FCL is intact. However, sectioning of the PCL after the FCL increases varus instability. Veltri et al²⁶ also reported that the varus rotation, which occurs with the sectioning of the posterolateral structures, is significantly increased with the PCL sectioning. Similarly, Gollehon et al² showed that isolated ACL and PCL sectioning only increased varus instability after the FCL and deep ligament complex sectioning also occurred. When comparing studies that sectioned the ACL first to those that sectioned the ACL after the lateral structures, we found the effect of sectioning the ACL on lateral opening under 12-N·m varus moment was different (0.31 vs 1.91 mm, respectively). Conversely, the results of this study did not demonstrate a significant difference between sectioning the ACL first or after posterolateral structures on lateral opening ($P = .387$). Biomechanical effects of ACL and posterolateral structures on varus rotation were reported in 2 previous studies, which did not include clinical varus stress radiograph evaluation.^{26,28} Veltri et al²⁶ reported

that the sectioning of the ACL after the sectioning of the posterolateral structures increased varus rotation in all degrees of flexion, while Wroble et al²⁸ reported that isolated ACL sectioning did not produce a significant increase in knee adduction. This discrepancy may be because of studies with low sample sizes and differences in biomechanical testing setups.

The results of this study showed that the mean increase in lateral opening after sectioning all states was 4.6 mm, and sectioning of the FCL contributed to 2.2 mm of this overall lateral opening. The effectiveness of varus stress radiographs in the diagnosis of posterolateral corner injuries has been reported in previous studies.^{5,11} Radiographs have been reported to be superior for quantifying lateral-sided injuries when compared with magnetic resonance imaging scans.¹³ On varus stress radiographs, lateral gapping of >2 mm compared with the contralateral intact side indicates FCL injury.^{12,13} By applying a standard 12-N·m varus moment, which has been compared with clinician-applied forces in prior studies,^{15,20} the current study demonstrated that an FCL injury results in a lateral opening of >2.2 mm, similar to what has been previously reported.^{12,13}

In the current study, the isolated ACL sectioning constituted a significant 1.3 mm of lateral opening. Clinically, this may be demonstrated by an isolated ACL injury causing mild lateral opening in varus stress radiographs. However, considering that at least 2 mm of gapping in varus stress radiographs indicates FCL injury,^{12,13} we conclude that an isolated ACL injury does not contribute to lateral opening to the degree of falsely indicating a lateral injury when stress radiographs are obtained. The results of this study also demonstrated that lateral gapping of >3 mm was achieved only after both the ACL and FCL were sectioned. In the ACL-first group, while isolated ACL sectioning produced 1.14 mm of lateral opening, the additional sectioning of the FCL caused a total of 3.62 mm of gapping. Additionally, lateral opening of >3 mm was only achieved when the ACL was added to the sectioning sequence in the FCL-first group. As such, from a clinical perspective, observing a lateral opening of >3 mm on varus stress radiographs may be indicative of an ACL injury in addition to an FCL injury.

While there were no significant differences in total lateral opening between the sectioning groups, a lateral gapping >4.2 mm could be indicative of an ACL in addition to grade 3 posterolateral knee injury. LaPrade et al¹⁵ previously reported that sectioning of the FCL, PLT, and PFL (representing a grade 3 posterolateral knee injury) caused 3.35 mm of lateral gapping with a 12-N·m varus moment and 4 mm of lateral gapping with a clinician-applied force. After the addition of ACL sectioning, this lateral gapping increased to 5.26 mm under a 12-N·m load and 6.55 mm with a clinician-applied force. In the current study, we similarly observed an increase in lateral gapping using a standard 12-N·m varus load of >4.2 mm after the addition of ACL sectioning to posterolateral corner sectioning.

Limitations

This study was not without limitations. One limitation was that the tested knees were nonpaired. In the current study,

sectioning models were created in the same knee in an intact state. Clinically, however, differences in lateral gapping may exist when comparing the injured knee to the normal contralateral side. Additionally, using the paired cadavers in the study and performing a different sectioning sequence on each side of the paired cadavers could be a more reliable way to reveal the effect of sectioning order. The lateral opening differences reported in previous studies compared with the current study may be due to the biomechanical setup. In contrast to previous studies using full lower limb cadavers, this study used knee specimens composed of the distal femur to the proximal tibia. The use of cadaveric knees instead of lower limbs was a limitation of this study in terms of clinical applicability compared with previous studies. However, in order to maintain the 12-N·m varus load in the knee joint as in the previous studies, we created the same moment force by considering the applied force and the distance of the point where it is applied to the joint.

Furthermore, it is known that there may be age-related changes in terms of size, structure, and function of the ACL.^{6,8,22,27} Because the majority of patients with knee ligament injuries are younger individuals, the use of cadavers with advanced age in this study can be considered another limitation that may affect clinical applicability. Although this study was a cadaveric study aiming to show the effect of sectioning the ACL on lateral opening under varus force, a clinician-applied force could also be added to establish the clinical application of the study findings. Lastly, the sample size was small. Considering the differences between the findings of similar studies in the literature, further studies including a larger number of specimens are needed.

CONCLUSION

ACL deficiency significantly increased lateral opening under varus stress, regardless of the sequence of injury. Although an isolated ACL injury did not contribute to lateral opening to the degree of falsely indicating a lateral injury, the effect of the ACL in addition to the lateral structures should be considered when using varus stress radiographs to evaluate knee injuries.

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