RESEARCH ARTICLE

Diagnostic Accuracy and Reliability of Dynamic Handheld Ultrasound Testing in Detecting Anterior Cruciate Ligament Tears: A Cadaveric Study

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Abstract

Objectives: Anterior cruciate ligament (ACL) injuries can go undetected in the initial encounter, and delayed diagnosis can cause instability and an elevated risk of osteoarthritis. We hypothesized that dynamic testing under handheld ultrasound assessments of ACL insufficiency offers high diagnostic accuracy and reliability.

Methods: Ten fresh-frozen knee specimens were evaluated in three conditions: (1) intact ACL, (2) complete ACL deficiency, and (3) ACL and Anterolateral ligament (ALL) deficiency. Dynamic testing under ultrasound was performed while simulating the Lachman test (tibial anterior translation with 0 and 100N, at 20 degrees knee flexion) and pivot shift test (internal rotation torque with 0 and 10Nm). The probe was placed at the anterior medial (AM) and lateral (AL) joint line, and anterior translation of the tibia (ΔD) relative to the femur was calculated. Intra-observer and inter-observer reliability were calculated, and receiver operating characteristic (ROC) curve analysis was performed for an ideal cutoff point for detecting knee instability.

Results: From the AM view, ACL-deficient and ACL+ALL-deficient conditions significantly increased ΔD of the tibia during anterior loading compared to the intact ACL condition. The median ΔD values of the tibia in AM view with anterior drawer load were 0.64 (-0.10, 2.67) mm (intact ACL), 4.76 (2.46, 7.21) mm (ACL deficiency), and 3.88 (2.08, 7.23) mm (ACL+ALL deficiencies). The area under the ROC curve identifying ACL deficiency was 0.89 (95%CI, 0.66-0.97) in the AM view with anterior loading simulating the Lachman test. The optimal cut-off value to distinguish between the intact and ACL-deficient condition for anterior tibial translation with loading was 2.6 mm (sensitivity=80%, specificity=90%).

Conclusion: Dynamic examination of the knee using portable handheld ultrasound from an AM view has high sensitivity and specificity in diagnosing ACL injury.

Level of evidence: V

Keywords: ACL, Athletic injuries, Injuries, Knee instability, Lachman test, Ultrasonography

Introduction

Anterior cruciate ligament (ACL) injuries are one of the most common knee injuries evaluated by sports medicine specialists, with over 200,000 cases occurring annually in the United States alone.[1,2] If left unrecognized and untreated, ACL injuries can contribute to functional impairment as well as result in damage to the meniscus and the articular cartilage, thereby increasing the patient's risk of developing osteoarthritis.[3-9] Therefore, timely detection and confirmation allow for prompt management and discussion of treatment options.[4,10] ACL injuries can go undetected, even though many patients present with pain early after the initial injury, and additional imaging studies, including magnetic resonance imaging (MRI), are recommended for a more accurate

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assessment and confirmation of ligament injuries. MRI utilization during the initial patient encounter is further limited by unavailability in resource-poor settings, excessive cost, and time required to undergo the study.[11] In addition, MRI cannot assess ACL function and the dynamic stability of the knee. This necessitates the search for more accessible, accurate imaging methods that can assist clinicians in the dynamic examination of the knee.

The Lachman test, pivot shift test, and anterior drawer test have been described as important dynamic assessments during physical examination to detect ACL injuries.[12]The Lachman test has been reported to have 69-87% sensitivity and 81-100% specificity, yet these tests require experience and expertise to detect ACL insufficiencies, while in most cases do not resolve the need for confirmation via imaging.[12,13] Moreover, the Lachman test categorizes knee laxity in 5 mm increments, and precise quantification with this test during physical examination remains difficult.

Ultrasound imaging has been shown to be highly accurate, affordable, and accessible for orthopaedic care settings, specifically for the assessment of soft tissue injuries.[14] Due to the oblique trajectory and deeper location of the ACL, examining it using ultrasound has been reported to be challenging for clinicians. Ultrasound imaging has been reported to be useful and precise in ACL injections, pre-operative graft assessment, and postoperative evaluation of muscles, fat pad, and articular cartilage; however, the outcomes highly rely on the expertise and experience of the examiner and MRI or arthroscopy are still needed to confirm and differentiate the severity of ACL injuries, partial, or complete ruptures.[15]

Studies on the use of ultrasound for dynamically examining the ACL and using quantitative methodology are scarce. Moreover, with the development of portable handheld ultrasound devices in recent years, concerns about the costs and accessibility of an imaging modality for knee examination have reduced; thus, if proven to be accurate, this technique can replace other more costly and hardly accessible tools, particularly in limited resource settings. In this biomechanical cadaver study, we aimed to evaluate the accuracy, sensitivity, and specificity of the portable handheld ultrasound in the evaluation of ACL insufficiency. We hypothesized that anterior ultrasound evaluation provides high reliability and diagnostic performance in the diagnosis of ACL insufficiency.

Materials and Methods

After receiving the institutional review board (IRB No. 2016P001295) approval, ten fresh-frozen cadaveric knee specimens amputated from mid-femur were used in this study. Using X-ray and arthroscopy, all specimens were confirmed to be free from pre-existing knee joint fractures, osteoarthritic changes, and ligamentous injuries by the senior author, who is a sports medicine specialist. All specimens were preserved at -20 °C and thawed for 24 hours at room temperature before testing. The femoral diaphysis was cut 30 cm from the joint line and its proximal end was fixed in a clamp with the foot resting on a table such that the knee joint was at 20° flexion [Figure 1]. Stability of the knee joint was tested under three conditions in the following order: (1) intact, (2) ACL deficient, and (3) ACL and Anterolateral ligament (ALL) deficient. The ACL-deficient condition was created using an arthroscopic technique, where all fibers were transected at the mid-substance of the ligament using a shaver and arthroscopic biter. The ALL-deficient condition was created after exposing the native ALL anterior to the lateral collateral ligament and transecting this completely at the mid-substance [Figure 2]. To evaluate knee stability, two loading tests were performed: anterior drawer loading and internal rotation (IR) torque. The Lachman test was created with a force of 100 N anteriorly on the tibia, via a Steinmann pin placed 3 cm distal to the tibial tuberosity. The pivot shift test was performed using internal rotation torque replicated by a 10–Nm internal tibial torque [Figure 1].

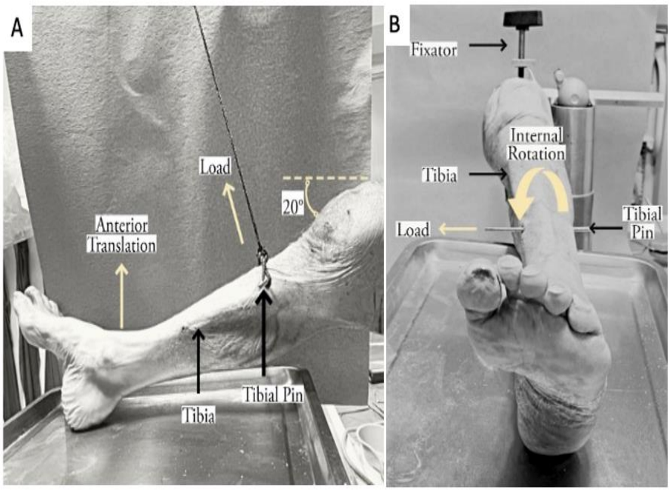

Figure 1. Experiments were performed with the knee joint in 20° flexion. (A) 100 N anterior drawer loading was applied to the tibia. (B) 10 Nm internal rotation torque was applied to the tibia

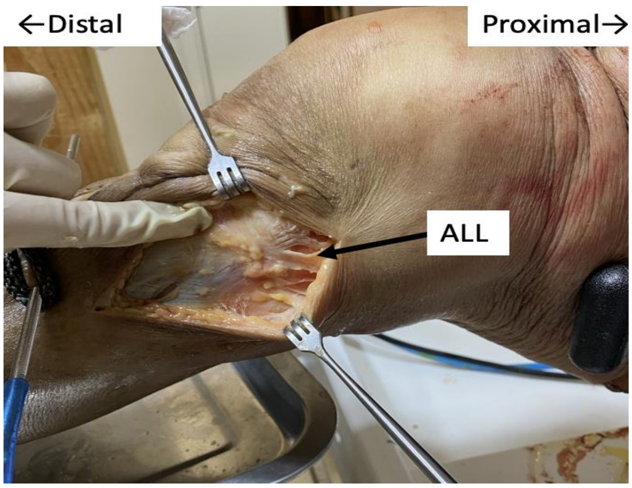

Figure 2. Surgically dissected specimen demonstrating the anterolateral ligament (ALL) of the knee

The ultrasound examination was performed by an orthopedic sports medicine surgeon using a portable handheld ultrasound device (iViz Air wireless handheld ultrasound, Fujifilm Co, Japan) connected wirelessly to a smart tablet (Sharp AQUOS Sense3) for visualizing the images. A linear-array probe with a frequency range of 5-10 MHz and a maximum scanning depth of 8 cm was used. The medial and lateral joint line was visualized from the anterior aspect by placing the transducer at the level of the joint line surface, parallel to the patellar tendon (PT).[16,17] In both the anterior medial (AM) view and anterior lateral (AL) views, imaging was performed at the most prominent aspect of the femoral condyles, keeping the femoral condyle edge and the anterior surface of the tibia visible as the bony landmarks. In each condition, images were obtained in the unloaded and loaded states.

The ultrasound images were imported into ImageJ (National Institutes of Health, Bethesda, MD) for measurements. Magnification scales embedded in the images were used for calibration and two lines tangent to the edge of the femoral condyle and the anterior surface of the tibia, respectively, were drawn. The distance between these lines was measured as D1 (Unloaded condition) and D2 (Loaded condition). The difference between D1 and D2 was taken as a measure of translation of the tibia (ΔD): ΔD= D2 - D1 [Figure 3 and 4]. Measurement of tibial rotation was calculated by dividing tibial translation in the AM view by tibial translation in the AL view under internal rotation torque.

Tibial rotation (mm) = ΔD in the AM view divided by ΔD in the AL view [Figure 3 and 4].

To evaluate inter-observer reliability, three observers, who were orthopaedic surgery clinical research fellows and were experts in the measurements, independently performed all measurements in five randomly selected specimens; for intra-observer reliability, all measurements were performed three times for five randomly selected samples by each observer on nonconsecutive days. Intra-observer and inter-observer reliability were assessed using the intraclass correlation coefficient (ICC) through a one-way analysis of variance and a two-way mixed-effects model with absolute agreement. Interpretation of the ICC values was calculated according to the guidelines proposed by Shrout as follows: 0.00–0.10, virtually none; 0.11–0.40, slight; 0.41–0.60, fair; 0.61–0.80, moderate; 0.81–1.00, substantial.[18]

Statistical Analysis

All variables were first assessed for normality using the Shapiro-Wilk and Kolmogorov–Smirnov test, and no significant deviations from normality were observed ($P > 0.05$ for all comparisons). A priori power analysis was conducted using G*Power (matched-pairs Wilcoxon signed-rank test, $\alpha = 0.05$) based on tibial translation means from prior work.[19] The analysis indicated that 7 matched specimen pairs are sufficient to achieve 95% power to detect the observed effect size. However, we intentionally included 10 matched specimens, exceeding that threshold to increase robustness. This decision was made to account for the high inter-specimen biological variability inherent in human cadaveric models (e.g., donor age, bone density, tissue integrity), which can influence measurement variance and effect estimation.[20,21]

The Wilcoxon Signed-Rank Test was used to compare tibial translation in intact ACL, ACL-deficient, and ACL+ALL-deficient conditions. Receiver operating characteristic (ROC) curve analysis was performed to calculate the ideal cut-off point (mm) for detecting instability during the anterior drawer test under ACL-deficient and ACL+ ALL-deficient conditions. The area under the ROC curve (AUC) was interpreted as follows: 0.5-0.6= fail, 0.6-0.7= poor, 0.7-0.8= acceptable, 0.8-0.9= excellent, and 0.9-1= outstanding. Statistical analysis was performed using SPSS for Windows (version 26.0, Armonk, NY, USA). The significance threshold was set at P-value < 0.05 for statistical analyses.

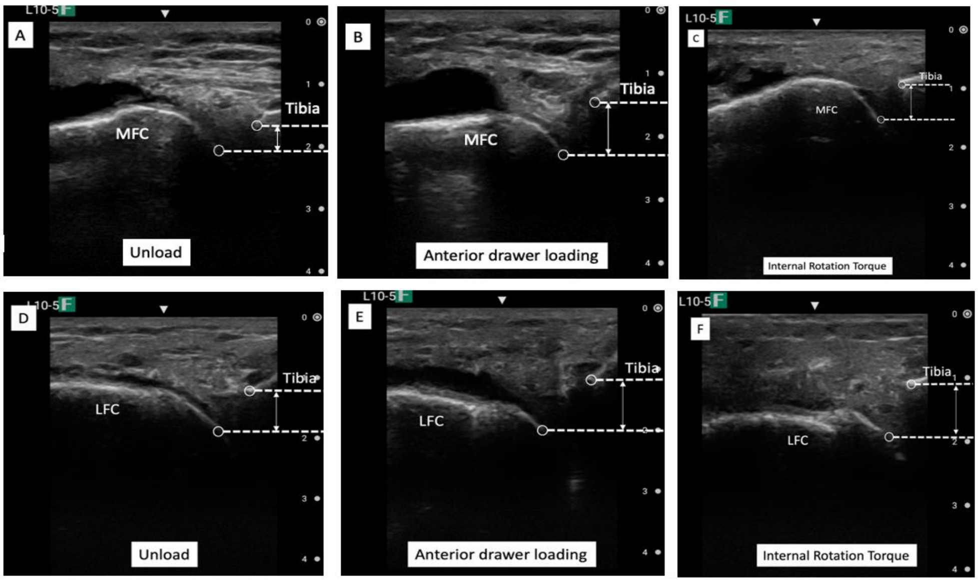

Figure 3. Ultrasonographic view of the knee demonstrating study procedures on an ACL tear specimen. (A) anteromedial view, no load applied, (B) anteromedial view, anterior drawer loading, (C) anteromedial view, internal rotation torque, (D) anterolateral view, no load applied, (E) anterolateral view, anterior drawer loading, (F) anterolateral view, internal rotation torque. MFC: Medial Femoral Condyle, LFC: Lateral Femoral Condyle

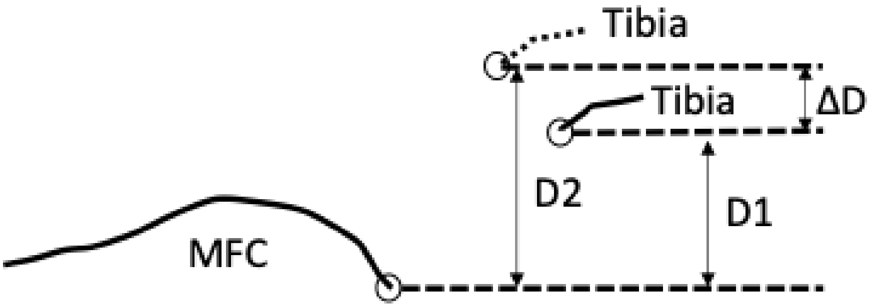

Figure 4. A schema showing the relative positions of the femoral condyle edge and the anterior edge of the tibia during ultrasound evaluation under various loading coditions. D1: Unload, D2: Loading (anterior drawer load or Internal rotation torque), ΔD: anterior translation of the tibia, ΔD = D2 – D1

Results

Ten knees were included in this study, with a gender distribution of seven males and three females, six left and four right knees. The mean age of the specimens was 66±8.1 years (range: 57 to 83 years).

Intra-observer reliability from the AM view (ICC=0.94; 95% CI, 0.90-0.97) and AL view (ICC=0.91; 95% CI 0.84-0.95) was substantial. Inter-observer reliability from the AM view was substantial (ICC= 0.86; 95% confidence interval, 0.70-0.93), but from the AL view was slight (ICC= 0.49; 95% confidence interval, 0.14-0.71).

From the AM view, both the ACL-deficient and ACL+ALL-deficient conditions showed significantly increased anterior translation of the tibia during anterior loading compared to the intact state ($P < .005$ and $P < .02$, respectively). Compared to the intact state, anterior tibial translation was increased by 3.5 mm in ACL-deficient and 4.1 mm in ACL+ALL-deficient conditions, respectively [Table 1, Figure 5A]. From the AM view, the difference in the anterior translation of the tibia between ACL-deficient and ACL+ALL-deficient conditions during anterior loading was not significant ($P = 0.50$). There was no significant difference in the anterior translation of the tibia in the AL view during the anterior loading tests for either ACL-deficient or ACL+ALL-deficient conditions [Figure 5B]. Furthermore, no difference was detected from either ultrasound view under internal rotation torque testing.

The results of ROC curve analysis for the AUC predicting ACL deficiency compared to the intact knee, and ACL+ALL from the deficiency compared to the ACL deficiency were summarized in [Table 2].

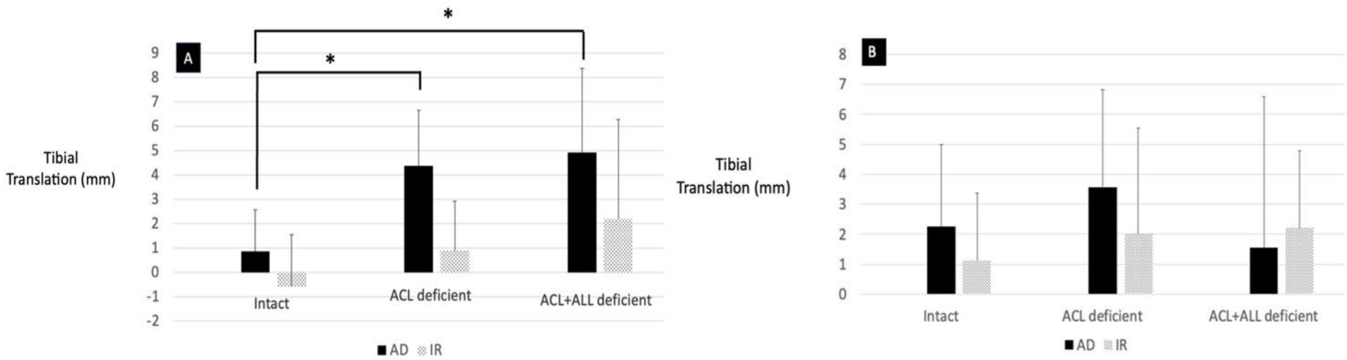

Figure 5. Comparison of tibial translation values obtained from different ultrasound views under various loading conditions (A) anterior medial view, (B) anterior lateral view. Asterisk shows a statistically significant difference. AD: Anterior drawer load, IR: Internal rotation torque

Table 1. Comparison of tibial translation across different ligament injury conditions using dynamic ultrasound assessment. Data are presented as median (interquartile range)

Probe placement	Specimen condition			*P*-value
	Intact (mm)	ACL deficient (mm)	ACL+ALL deficient (mm)	

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Table 1. Continued

Lachman test	*Anteromedial*	0.64 (-0.10, 2.67)	4.76 (2.46, 7.21)	3.88 (2.08, 7.23)	0.005*, 0.02†, 0.50‡
	Anterolateral	1.54 (0.80, 4.88)	2.04 (1.03, 6.09)	0.18 (-2.17, 4.40)	0.57*, 0.44†, 0.13‡
Pivot shift test	*Anteromedial*	-.22 (-2.01, 1.39)	1.24 (0.01, 2.75)	1.12 (-2.44, 3.67)	0.13*, 0.33†, 0.57‡
	Anterolateral	1.82 (-1.23, 2.81)	2.12 (-1.28, 5.47)	1.68 (-1.05, 3.23)	0.64*, 0.72†, 0.57‡

Abbreviations: ACL, Anterior Cruciate Ligament; ALL, Anterolateral Ligament
* Intact vs ACL Deficient; † Intact vs ACL+ALL Deficient; ‡ ACL Deficient vs ACL+ALL Deficient

Table2. The diagnostic performance of anterior medial ultrasound evaluation during the Lachman test for ACL injuries.

Injury Status	Cut-off value (mm)	AUC (95% CI)	Accuracy (%)	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Intact vs ACL	2.6	0.89 (0.66- 0.97)	85	80	90	88.9	81.8
ACL vs ACL+ALL	8.6	0.50 (0.31-0.69)	58	15	100	100	91.4

AUC, Area under the curve; CI, Confidence Interval; %, Percentage; mm, Millimetres; PPV, Positive Predictive Value; NPV, Negative Predictive Value; ACL, Anterior Cruciate Ligament; ALL, Anterolateral Ligament

Discussion

In this study, we found that the use of portable handheld ultrasound imaging from the anterior aspect of the knee for the detection of ACL insufficiency is a useful approach with high sensitivity and specificity, accuracy, and reproducibility. This imaging technique is low in cost, accessible, accurate, with no radiation, and can be a promising tool, especially for limited-resource settings, to improve the quality of healthcare and assist clinicians with the process of decision-making and management of patients with ACL injuries.

A recent clinical study reported that posterior knee ultrasound in the prone position could diagnose patients with ACL injuries with 96-97% sensitivity and 84-98% specificity.[22,23] A meta-analysis reported that ultrasonographic examination in the prone position can be used as an excellent diagnostic tool for ACL injury with a sensitivity of 88% and specificity of 96%.[24] Given that most of these studies lacked a methodology that dynamically examines the ACL, and none have used the newly developed portable handheld ultrasound devices, our study is the first biomechanical study to determine the sensitivity, specificity, and AUC-based cut-off values for the anterior ultrasonographic approach for detecting ACL injuries while confirming the extent of both ACL and ALL injuries. Furthermore, evaluation from the anterior aspect of the knee makes it possible for the patient to be examined in the supine position, allowing both outpatient and operating room assessments to be performed without any positional changes.[15,25]

The use of other dynamic testing measures, including the KT-1000 arthrometer (Medmetric Corp, San Diego, USA) or the Knee Laxity Tester (Stryker Corp, Kalamazoo, MI), has been described to evaluate knee stability quantitatively, with side-to-side differences >3mm indicating ACL insufficiency.[26] Similarly, in our study, the threshold for ACL deficiency was 2.6 mm compared to the intact knee upon ultrasound evaluation. It has been reported that measurements obtained with arthrometers vary from examiner to examiner and should be repeated by the same examiner whenever possible.[27] Additionally, previous reports have stated that arthrometer measurements could not be generalized from one instrument to another because of the variability among the models handled.[28] In contrast, ultrasound imaging makes it possible to evaluate the knee joint instability dynamically and quantitatively based on visualization, in a portable fashion.[26] Thus, another advantage of the approach described in our study is that it has the potential to be used for postoperative follow-up and functional evaluation as a method for quantitative evaluation of instability. Further studies are needed to identify the role of ultrasound-based evaluations before and after ACL reconstruction in the assessment of ACL function.

Multiple studies have found that the Lachman test can diagnose ACL injuries with a sensitivity ranging from 77% to 85%.[29-31] Anne et al. also reported a specificity of 94% for the Lachman test, a sensitivity of 92%, and a specificity of 91% for the anterior drawer test with high diagnostic accuracy.[29] Despite these numbers, it is estimated that ACL injuries are correctly diagnosed at the initial visit in <20% of patients.[9,10] This is likely because of many factors, such as the experience of the measurer, which can affect the reliability of the sensitivity and specificity of each test.[32,23] Therefore, a physical examination alone is not sufficient to make a diagnosis. In this study, AUC was used to calculate cut-off values during the anterior loading test. The results showed that the AM view evaluation was an excellent diagnostic method with a sensitivity of 80%, specificity of 90%, and accuracy of 85% when 2.6 mm of anterior tibial translation was seen compared to intact. A more accurate diagnosis and confirmatory method can be expected if an ultrasound evaluation is added to the physical examination.[22]

In this study, the ACL+ALL injury model was created in addition to the ACL injury and evaluated in the same method. However, in the ACL+ALL injury model, there was no significant difference in the amount of anterior tibial translation during IR torque compared to intact or ACL injury models alone. Previous reports stated that tibial rotational instability is increased when the ALL was transected, whereas other biomechanical studies reported that ACL+ALL injury does not increase anterior tibial translation and internal rotation compared to the ACL tear condition.[33,34] The reason for this may be that the primary restraint to anterior instability is the ACL, and the restriction to IR is the iliotibial ligament, while the role of the ALL is relatively small.[35-37] While there was no significant difference between ACL and ACL+ALL in the amount of tibial translation during IR loading in the AM view and AL view evaluations, respectively, the values in the AM/AL ratio were significantly different between ACL injury and ACL+ALL injury in our study.

The reason for the larger AM/AL ratio in ACL+ALL-deficient compared to ACL-deficient may be a combination of anterior tibial translation as well as increased IR, which causes the medial side to move relatively more posteriorly than the lateral side. This result may provide insight for further evaluation of detecting additional ALL injuries. Although not directly evaluated in this study, previous reports have indicated that the ultrasound is useful for directly describing ALL conditions, and the dynamic assessment of rotational instability on ultrasound may serve as a future direction for more accurate evaluation of ALL insufficiency in the setting of ACL injury.[38,39]

There are some limitations to our study. Since muscle contraction due to pain avoidance was not a factor, the results may not be directly applicable to clinical studies. While standardizing the force for testing is commonly done for research purposes, it might not be a practical choice clinically. Appropriate training and experience are also considered necessary to diagnose ACL injuries using ultrasound.[40] As this was a cadaveric study, the presence of prior injuries or symptoms in the knee could not be confirmed. We acknowledge that our sample size of 10 paired specimens is inadequate for precise ROC curve analysis or formal regression modeling. These limitations constrain the generalizability of our ROC findings, including sensitivity and specificity. Future clinical studies are needed to validate our findings.

Conclusion

The present study showed that dynamic portable handheld ultrasound assessment of the ACL has high reproducibility, sensitivity, and specificity in diagnosing ACL tears. Based on the results of this study, ultrasound-guided Lachman testing may be a useful examination method for knee injuries with suspected ACL tears and should be further explored as an evaluation method for the knee before and after ACL reconstruction. As an accessible, low-cost, low-risk, and accurate method, portable handheld ultrasonography has the potential to replace the current costly, time-consuming, and less accessible imaging modalities, such as MRI, in the diagnosis and confirmation of soft tissue injuries, including ACL, particularly in underprivileged settings.

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Declaration of Informed Consent: The study was done on cadavers, and consenting was waived by the institutional review board.

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