Dynamic Ultrasound Can Accurately Quantify Severity of Medial Knee Injury: A Cadaveric Study

Rohan Bhimani, M.D., M.B.A., Bart Lubberts, M.D., Ph.D., Christopher W. DiGiovanni, M.D., and Miho J. Tanaka, M.D.

Purpose: To quantify the severity of medial knee injuries based on medial compartment gapping as measured by stress ultrasonography. Methods: In 8 cadaveric knees, the distance between the medial tibial and femoral condyles was measured using ultrasonography. These measurements were obtained in the intact state and repeated after open sequential transection of the superficial medial collateral ligament (sMCL), deep medial collateral ligament (dMCL), posterior oblique ligament (POL), and arthroscopic transection of the anterior cruciate ligament (ACL). Knees were evaluated at 0° and 20° of knee flexion using the Telos device under 0 N and 100 N of valgus force. Receiver operating characteristic curve analysis and the DeLong test were used to determine whether measurements could distinguish between successive severity of MCL injury after identifying the optimal cutoff value for each injury state. Results: Of the 8 cadaveric knees included in this study, 3 were male and 5 were female. The mean age was 58.11 years (range 48-82 years). When measured using ultrasonography at 20° knee flexion with valgus load, the medial tibiofemoral distance significantly increased with increasing severity of medial knee injury (P values ranging from 0.049 to <0.001). The optimal cutoff values for distinguishing between an intact knee and sMCL injury were 8.3 mm (area under the curve [AUC] = 0.98), between sMCL and dMCL injury 9.9 mm (AUC = 0.89), dMCL and POL 16.7 mm (AUC = 0.88), and POL and ACL 18.6 mm (AUC = 0.84). When we compared combined intact and sMCL-transected stages with dMCL-transected stage, the optimal cut-off point to differentiate stable from unstable injuries was equal to 13.8 mm of medial tibiofemoral distance (AUC = 0.97; sensitivity = 100%; specificity = 94.1%). Conclusions: Dynamic ultrasonographic assessment can accurately quantify the severity of medial knee ligament injury based on medial compartment gapping. In our study, we found medial tibiofemoral distance >13.8 mm at 20° knee flexion under valgus force indicates the presence of dMCL injury with a diagnostic accuracy of 0.97. Clinical Relevance: Dynamic ultrasonography can quantify severity of medial knee injury without radiation and at point of care in multiple clinical settings.

The medial collateral ligament (MCL) is a major stabilizer of the medial knee joint and is the most commonly injured knee ligament as a result of valgus force on the knee.1-4 Injury to the components of the MCL, namely the superficial medial collateral ligament (sMCL), the posterior oblique ligament (POL), and the deep medial collateral ligament (dMCL), frequently occurs due to combined valgus—external rotational forces on the tibia.3,5 While most MCL injuries can still be managed nonoperatively with a good functional outcome,5,6-8 reconstruction is indicated in cases of persistent grade 3 medial knee laxity.1,9,10 Inadequately treated medial knee injuries may lead to persistent instability, which in turn may result in failure of meniscal repairs and cruciate reconstructions, in addition to articular cartilage damage.11,12 Thus, accurate diagnosis of the severity and management of medial knee injuries is critical.
Physical examination remains a mainstay to quantify medial knee injuries. Clinical stress maneuvers such as laxity testing allow MCL injuries to be classified based on the amount of medial compartment opening in the setting of an applied valgus force in full extension as well as at 20° to 30° of knee flexion.13,14 Laxity grades 1+ to 3+ are commonly used to grade the severity and laxity of an injured medial knee. Laxity grade 1+ indicates a mild opening (0-5 mm), grade 2+ indicates a moderate opening (5-10 mm), and grade 3+ indicates opening >10 mm.13,14 Pain and muscle spasm in an acute setting may obscure accurate grading of MCL injuries, especially in the presence of concomitant injuries. Moreover, the accuracy of this test in quantifying MCL injuries is highly susceptible to the examiner’s subjective interpretation and has proven to be unreliable, especially in an acute setting.15 Diagnostic confirmation has thus often relied on provocative stress maneuvers under imaging.15,16 The current gold standard modality for evaluating medial knee injury is magnetic resonance imaging (MRI); however, because medial knee instability is a dynamic process, assessing the appearance of the medial knee ligaments on static MRI can result in high false-negative rates.8,15 Furthermore, it does not allow for a comparison with the contralateral healthy side. Radiographs preferably with stress maneuvers such as valgus stress test routinely have been used to evaluate the competence of the medial knee ligaments due to their widespread use and ability to provide a contralateral comparison.16 The combination of poor portability and radiation exposure, however, may limit the role of radiographic evaluation.

In recent years, dynamic portable ultrasonography is increasingly being applied to musculoskeletal conditions.17-19 Apart from almost universal portability, other benefits of this modality include its low cost, lack of radiation, ready availability at the point of care, and ability to easily visualize and compare contralateral healthy anatomic structures under applied stress. Previous studies have demonstrated that ultrasonography is a reliable and accurate tool for qualitatively assessing medial knee injuries and that it is comparable with MRI in assessing medial knee ligaments.17,20 The purpose of the study was to quantify the severity of medial knee injuries based on medial compartment gaping as measured by stress ultrasonography. We hypothesized that stress ultrasound measurements would significantly increase with increasing severity of medial sided knee injury when compared with the intact state.

Methods

Specimen Preparation and Dissection

Eight fresh-frozen unpaired, above-knee cadaveric specimens cadaveric knee specimens were used in this study. Each knee had been amputated at the mid-to-proximal femur and included the foot distally. Before the experiment, each knee was arthroscopically (Synergy 4K System; Arthrex, Naples, FL) and radiographically evaluated (Cios Alpha mobile C-Arm, Siemens, Munich, Germany). Specimens were excluded if there were any signs of previous surgeries, fractures, ligamentous injuries, or pre-existing knee osteoarthritis, and all specimens in this sample ultimately were included. Before biomechanical testing, specimens were thawed at room temperature and soft tissues were preserved to mimic in vivo conditions. The femur was secured to allow knee flexion up to 20°. Knees were positioned in the TELOS device (Telos GmbH, Laubscher, Holstein, Switzerland) and a valgus force was applied at the level of tibial tuberosity. Two medial counter supports were positioned, one on the femur 10 cm proximal to the medial joint line and the other on the tibia at the midshaft. Two standardized loading conditions were created using the Telos device: (1) Unloaded (0 N of force), and (2) loaded with 100 N of valgus force21 (Fig 1).

Portable Ultrasound Technique

The distance between the medial tibia and medial femur was assessed using a portable ultrasound device (2D, grayscale B mode complete ultrasound; Butterfly iQ, Butterfly Network Inc, Guilford, CT) (Fig 1). For standardized measurements the medial epicondyle was palpated, and the probe was positioned in a longitudinal direction, perpendicular to the medial joint line to visualize the medial femoral condyle and the medial tibial plateau in one image. Ultrasound images were obtained in the unloaded and loaded conditions at 0° and 20° of knee flexion, respectively, using a handheld goniometer to measure knee flexion. Ultrasound images were obtained by an orthopaedic surgeon experienced in using musculoskeletal ultrasound.

After we obtained ultrasound images from the intact knees, each specimen underwent sequence of ligament transection based on a previous study by LaPrade et al.16 Each knee was subjected to the same sequence of ligamentous transections and was assessed under ultrasound after each transection. A medial skin incision was made from the medial epicondyle extending distal to the joint line, and surgical dissection through layer 1 was performed to identify the MCL and the POL. The sMCL was transected first, then the dMCL, followed by POL, and finally the anterior cruciate ligament (ACL) (Fig 2). After sequential transectioning of the MCL and the POL, the ACL was transected arthroscopically.

Measurements were performed on the ultrasound images using Image J (version 1.8.0; National Institutes of Health, Bethesda, MD). The magnification scale embedded in each image allowed accurate calibration
of the measurements. All images were analyzed by a fellowship-trained sports medicine surgeon and a fellowship-trained arthroplasty surgeon. The medial tibiofemoral distance was defined by measuring the closest perpendicular distance between the central aspect of the medial femoral condyle and the corresponding medial tibial plateau (Fig 3).19

**Fluoroscopic Technique**

Fluoroscopic assessment was performed simultaneously during the aforementioned intact and sequential ligamentous transection states. True anteroposterior radiographs (anteroposterior view) were taken perpendicular to the joint line at 0° and 20° of knee flexion in both the unloaded and loaded states. To perform the measurements, fluoroscopic images were imported into Image J. The medial tibiofemoral distance was calculated by measuring the closest perpendicular distance between the central aspect of the medial femoral condyle and the corresponding medial tibial plateau (Fig 4).16

**Sample Size Calculation and Statistical Analysis**

A sample size calculation was carried out based on our null hypothesis that there is no difference in ultrasound measurements of medial tibiofemoral distance between a stable and unstable injury using a paired t test. In a previous study, LaPrade et al.16 radiographically evaluated the medial tibiofemoral gap after transectioning of the distal sMCL and after transectioning of both distal sMCL and meniscotibial ligament at 20° of knee under 10 Nm of valgus load. They reported that the mean ± standard deviation distance for the medial compartment gap after transectioning of distal sMCL and after transectioning of distal sMCL + meniscotibial ligament was 9.1 ± 1.2 mm and 11.5 ± 2.4 mm, respectively. To achieve 80% statistical power for detecting a difference of 2.4 mm (9.1 ± 1.2 mm vs 11.5 ± 2.4 mm, 0.6 correlation) between stable and an unstable injury with an overall 2-tailed Type 1 rate of 5%, we needed 8 knee specimens in total. The sample size was calculated using G*Power, Version 3.1.9.2 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany).

All measurements were reported as percentage or mean and standard deviation in millimeters. The medial tibiofemoral distance was described to the nearest 0.1 mm. Normality of the data was assessed using the Kolmogorov–Smirnov test and the Shapiro–Wilk test. One-way analysis of variance with post hoc Tukey honestly significant difference was used to test for significant differences in medial tibiofemoral distance between each stage of ligament transection, and at each sequential stress measurement. The receiver operating characteristic

---

**Fig 1.** The experimental setup demonstrates a left knee mounted in a Telos device, which was used to perform valgus stress tests under 100 N force at 0° and 20° of knee flexion. The portable ultrasound probe is positioned perpendicular to the medial joint line over the medial collateral ligament.

**Fig 2.** (A) Medial view of the left knee with superficial medial collateral ligament identified and isolated. (B) The superficial medial collateral ligament is transected.
(ROC) curve analysis with an area under the curve (AUC) and the DeLong test were used to determine whether measurements could distinguish between successive severity of MCL injury for both ultrasoundography and fluoroscopy. Moreover, the differences between the ROC curves of each imaging technique also were determined using the DeLong test. In general, an AUC of 0.5 suggests no discrimination (i.e., ability to diagnose patients with and without the disease or condition based on the test), 0.7 to 0.8 is considered acceptable, 0.8 to 0.9 is considered excellent, and more than 0.9 is considered outstanding. Youden’s J statistic was calculated to determine the optimal cutoff value for each injury state. To investigate the correlation between ultrasound and fluoroscopic measurements, the Pearson correlation coefficient was calculated. Interpretation to indicate the strength of correlation was as follows: slight correlation ($r < 0.2$), low correlation ($r = 0.3-0.4$), moderate correlation ($r = 0.4-0.7$), high correlation ($r = 0.7-0.9$), and very high correlation ($r = 0.9-1.0$). A $P$ value < .05 was considered as statistically significant. SPSS, version 26.0, was used to analyze the data (IBM SPSS Statistics, Armonk, NY).

Intraclass correlation coefficients (ICC) were calculated to assess inter- and intrarater reliability through a 2-way mixed effects model with absolute agreement. The intrarater reliability was calculated by having a single observer perform each measurement twice on
Table 1. Medial Tibiofemoral Distance Based on Ultrasonographic Evaluation Comparing Intact State With Subsequent Transection

| Stage | Unloaded | Loaded (100 N) | Unloaded | Loaded (100 N) |
|-------|----------|---------------|----------|---------------|
|       | 0° Knee Flexion | 20° Knee Flexion |       |               |
|       | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm |
| Intact | 6.5 ± 1.1 | 6.6 ± 1.2 | 7.0 ± 1.1 |       |
| sMCL  | 7.3 ± 1.5 | 10.8 ± 2.4* | 8.2 ± 2.0 | 10.9 ± 1.8* |
| dMCL  | 10.7 ± 2.2* | 14.8 ± 3.2* | 11.3 ± 2.4* | 15.7 ± 2.4* |
| POL   | 11.9 ± 2.3 | 15.6 ± 3.6 | 14.4 ± 1.9 | 18.6 ± 3.5* |
| ACL   | 14.1 ± 2.5 | 20.3 ± 2.7* | 16.3 ± 2.0 | 22.8 ± 3.3* |

ACL, anterior cruciate ligament; dMCL, deep medial collateral ligament; POL, posterior oblique ligament; SD, standard deviation; sMCL, superficial medial collateral ligament.

*Statistically significant change compared with the previous transected stage.

**Table 2.**
| Stage | Unloaded | Loaded (100 N) | Unloaded | Loaded (100 N) |
|-------|----------|---------------|----------|---------------|
|       | 0° Knee Flexion | 20° Knee Flexion |       |               |
|       | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm |
| Intact | 6.5 ± 1.1 | 6.6 ± 1.2 | 7.0 ± 1.1 |       |
| sMCL  | 7.3 ± 1.5 | 10.8 ± 2.4* | 8.2 ± 2.0 | 10.9 ± 1.8* |
| dMCL  | 10.7 ± 2.2* | 14.8 ± 3.2* | 11.3 ± 2.4* | 15.7 ± 2.4* |
| POL   | 11.9 ± 2.3 | 15.6 ± 3.6 | 14.4 ± 1.9 | 18.6 ± 3.5* |
| ACL   | 14.1 ± 2.5 | 20.3 ± 2.7* | 16.3 ± 2.0 | 22.8 ± 3.3* |

ACL, anterior cruciate ligament; dMCL, deep medial collateral ligament; POL, posterior oblique ligament; SD, standard deviation; sMCL, superficial medial collateral ligament.

*Statistically significant change compared with the previous transected stage.

**Table 3.**
| Stage | Unloaded | Loaded (100 N) | Unloaded | Loaded (100 N) |
|-------|----------|---------------|----------|---------------|
|       | 0° Knee Flexion | 20° Knee Flexion |       |               |
|       | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm | Mean ± SD, Intact State, mm |
| Intact | 6.5 ± 1.1 | 6.6 ± 1.2 | 7.0 ± 1.1 |       |
| sMCL  | 7.3 ± 1.5 | 10.8 ± 2.4* | 8.2 ± 2.0 | 10.9 ± 1.8* |
| dMCL  | 10.7 ± 2.2* | 14.8 ± 3.2* | 11.3 ± 2.4* | 15.7 ± 2.4* |
| POL   | 11.9 ± 2.3 | 15.6 ± 3.6 | 14.4 ± 1.9 | 18.6 ± 3.5* |
| ACL   | 14.1 ± 2.5 | 20.3 ± 2.7* | 16.3 ± 2.0 | 22.8 ± 3.3* |

ACL, anterior cruciate ligament; dMCL, deep medial collateral ligament; POL, posterior oblique ligament; SD, standard deviation; sMCL, superficial medial collateral ligament.

*Statistically significant change compared with the previous transected stage.

Results

Eight cadaveric knees were included in this study. The mean cadaveric age was 58 ± 11 years (range 48-82 years), with 3 being male and 5 being female. The mean time from death to cadaver dissection was 5 ± 2 days (range 0-10 days). The mean cadaveric age was 58 ± 11 years (range 48-82 years). The mean cadaveric age was 58 ± 11 years (range 48-82 years). The mean cadaveric age was 58 ± 11 years (range 48-82 years). The mean cadaveric age was 58 ± 11 years (range 48-82 years). The mean cadaveric age was 58 ± 11 years (range 48-82 years).
Table 2. Medial Tibiofemoral Distance Based on Fluoroscopic Evaluation Comparing Intact State With Subsequent Transection

| Stage  | Unloaded 0° Knee Flexion | Loaded (100 N) Unloaded 0° Knee Flexion | % Change | Difference Compared With Intact State, mm | % Change | Difference Compared With Intact State, mm | % Change | Difference Compared With Intact State, mm | % Change | Difference Compared With Intact State, mm |
|--------|--------------------------|-----------------------------------------|----------|-------------------------------------------|----------|-------------------------------------------|----------|-------------------------------------------|----------|-------------------------------------------|
| Intact | 5.7 ± 0.3                | 6.2 ± 0.3                               | 2.5 ± 0.4 | 6.2 ± 0.3                                 | 3.9 ± 0.4 | 6.1 ± 0.6                                 | 1.0 ± 0.6 | 6.9 ± 0.7                                 | 2.3 ± 1.2 | 33.3                                      |
| sMCL   | 6.2 ± 0.4                | 8.3 ± 0.9*                              | 2.1 ± 0.2 | 6.6 ± 0.6                                 | 0.5 ± 0.1 | 8.2 ± 0.1                                 | 4.3 ± 0.3 | 14.6 ± 1.7*                               | 7.7 ± 1.6 | 111.6                                     |
| dMCL   | 8.1 ± 1.0*               | 10.4 ± 1.6*                             | 2.4 ± 0.2 | 8.9 ± 1.0*                                | 2.8 ± 0.4 | 45.9 ± 1.2*                               | 14.6 ± 1.7 | 111.6                                     |
| POL    | 8.9 ± 1.5                | 11.8 ± 1.8*                             | 3.2 ± 0.4 | 10.4 ± 1.3*                               | 4.3 ± 0.3 | 70.5 ± 1.7*                               | 5.5 ± 0.4 | 17.2 ± 2.2*                               | 10.6 ± 3.2 |
| ACL    | 10.3 ± 2.0               | 15.3 ± 1.8*                             | 4.6 ± 0.4 | 11.6 ± 2.1*                               | 5.5 ± 0.2 | 90.2 ± 1.6*                               | 15.7 ± 2.0 | 153.6                                     |

ACL, anterior cruciate ligament; dMCL, deep medial collateral ligament; POL, posterior oblique ligament; SD, standard deviation; sMCL, superficial medial collateral ligament.

*Statistically significant change compared with the previous transected stage.

Discussion

The most important finding of this study was that...
for ultrasound measurements showed no difference from the AUC for fluoroscopy measurements (P values ranging from .207 to .848). Thus, our study highlights that ultrasonography is a promising suitable alternative for quantifying medial knee instability at point of care without radiation exposure to the patient or practitioner.

Although previous studies have evaluated the utility of ultrasonography in qualitatively assessing medial knee ligaments, few have elucidated the role of stress ultrasonography in quantifying medial knee instability. Ghosh et al. \(^{17}\) compared the efficacy of point-of-care ultrasonography without dynamic stress to diagnose injuries to the medial knee compartment when compared with MRI in an orthopaedic outpatient clinic. In this prospective observational study, the authors evaluated 9 patients with medial knee pain using ultrasonography before their scheduled MRI. On ultrasonography, the degree of MCL tear was graded from 1 to 3 based on observation of the fibers, with grade 1 (mild) representing stretching of the ligament without discontinuity of the fibers and associated edematous changes, grade 2 (moderate) representing partial disruption of the ligament, and grade 3 (severe) representing complete discontinuity of the ligament fibers and/or retraction. When compared with MRI, they found ultrasound to have a 67% sensitivity and 83% specificity, with a positive predictive value of 67% and negative predictive value of 83% for MCL tears. In our study, dynamic assessment of medial knee instability was performed, which may serve as a useful tool for detecting instability more accurately and with less error. Furthermore, we based our findings on known anatomic injuries to allow for reliable diagnosis of injury severity. Further clinical studies are needed to determine the utility and applicability of our ultrasound measurement technique in the indications and techniques for medial knee reconstruction.

In a previous cadaveric study, Slane et al. \(^{25}\) compared the medial tibiofemoral gap in 20° of knee flexion in intact knees under 0 and 10 Nm of valgus force to mimic fluoroscopy (mFluoro) images created from segmented computed tomography scans. They found the medial tibiofemoral distance to be 8.7 ± 2.4 mm and 10.7 ± 2.2 mm when subjected to 0 N and 100 N of valgus force, respectively. In addition, they found no significant differences in between ultrasound and mFluoro measurements. Similarly, Lutz et al. \(^{19}\) prospectively evaluated the medial tibiofemoral distance in

---

**Table 3. Area Under ROC Curves (AUC) and Cut-off Values of Medial Tibiofemoral Distance Based on Ultrasonographic Evaluation for Each Successive Injury State**

| Medial Tibiofemoral Distance At 20° pf Knee Flexion Under Valgus Force | Cut-off value, mm | AUC | 95% CI | Overall Accuracy, % | Sensitivity, % | Specificity, % |
|---|---|---|---|---|---|---|
| Stage 0 vs stage 1 | 8.3 | 0.98 | 0.77-1.0 | 93.8 | 87.5 | 100 |
| Stage 1 vs stage 2 | 9.9 | 0.89 | 0.64-0.99 | 91.3 | 82.5 | 100 |
| Stage 2 vs stage 3 | 16.7 | 0.88 | 0.63-0.99 | 87.5 | 87.5 | 87.5 |
| Stage 3 vs stage 4 | 18.6 | 0.84 | 0.58-0.97 | 87.5 | 75 | 100 |
| Stable vs unstable injuries | 13.8 | 0.97 | 0.82-1.00 | 97.1 | 100 | 94.1 |

ACL, anterior cruciate ligament; AUC, area under the curve; CI, confidence interval; dMCL, deep medial collateral ligament; %, percentage; POL, posterior oblique ligament; sMCL, superficial medial collateral ligament; stable injuries, combined stage 0 and stage 1; stage 0, intact state; stage 1, transectioning of sMCL; stage 2, transectioning of sMCL and dMCL; stage 3 transectioning of sMCL, dMCL, and POL; stage 4, transectioning of sMCL, dMCL, POL, and ACL; unstable injuries, stage 2.
Table 4. Area Under ROC Curves (AUCs) and Cut-off Values of Medial Tibiofemoral Distance Based on Fluoroscopic Evaluation for Each Successive Injury State

| Force                  | Cut-off Value, mm | AUC         | 95% CI      | Overall Accuracy, % | Sensitivity, % | Specificity, % |
|-----------------------|-------------------|-------------|-------------|---------------------|----------------|----------------|
| Stage 0 vs stage 1    | 7.6               | 0.96        | 0.88-1.0    | 93.8                | 100            | 87.5           |
| Stage 1 vs stage 2    | 10.9              | 0.97        | 0.74-1.0    | 93.8                | 87.5           | 100            |
| Stage 2 vs stage 3    | 13.9              | 0.90        | 0.71-1.0    | 81.3                | 62.5           | 100            |
| Stage 3 vs stage 4    | 16.1              | 0.86        | 0.65-0.99   | 87.5                | 87.5           | 87.5           |
| Stable vs unstable    | 10.9              | 0.98        | 0.83-1.0    | 93.8                | 87.5           | 100            |

ACL, anterior cruciate ligament; AUC, area under the curve; CI, confidence interval; dMCL, deep medial collateral ligament; %, percentage; POL, posterior oblique ligament; SMCL, superficial medial collateral ligament; stable injuries, combined stage 0 and stage 1; stage 0, intact state; stage 1, transactioning of sMCL; stage 2, transactioning of sMCL and dMCL; stage 3 transactioning of sMCL, dMCL, and POL; stage 4, transactioning of sMCL, dMCL, POL, and ACL; unstable injuries, stage 2.

79 healthy knees. Using the Telos device, the assessment was performed at 0° and 30° of knee flexion under 0 N and 150 N of valgus load. The authors reported that at 30° of knee flexion, the mean medial joint distance was 6.1 ± 1.1 mm and 7.8 ± 1.2 mm in the unloaded and loaded states, respectively. In our study, we used similar landmarks for measurement during ultrasound evaluation and found the medial tibiofemoral distance to be 6.6 ± 1.2 mm and 7.0 ± 1.1 mm at 20° of knee flexion with valgus forces of 0 N and 100 N, respectively. In addition, under a valgus force of 100 N at 20° of knee flexion, we also found an increase in medial tibiofemoral distance to 10.9 ± 1.8 mm and 15.7 ± 2.4 mm in isolated SMCL and combined SMCL and dMCL injury, respectively. Moreover, when differentiating between combined intact and SMCL transected state (stable injuries) to DMC transected state (unstable injuries), we found that 13.8 mm of medial tibiofemoral distance (AUC = 0.97; sensitivity = 100%; specificity = 94.1%) was the optimal threshold to distinguish stable from unstable injuries. Thus, our study underscores that ultrasonography is able to discern a stable from an unstable medial knee joint with high accuracy. Further clinical studies are recommended to study the utility of ultrasound-based assessments in the evaluation and management of MCL injuries in the clinical setting.

The assessment of MCL reconstruction and repair techniques could benefit from the measurement of medial compartment gap, as improvements in technique have been linked to better results. Lutz et al. recently used ultrasonography and clinical examination to evaluate treatment outcomes of combined acute ACL and MCL injuries. In this retrospective study, 40 patients with ACL and MCL injuries were equally assigned to 1 of 2 treatment groups. Patients in group 1 underwent ACL reconstruction with concurrent MCL repair, whereas patients in group 2 underwent ACL reconstruction with nonoperative MCL management. Grade II MCL injuries with dislocated tibial or femoral avulsions and grade III MCL ruptures were repaired in their study, whereas grade II injuries without dislocated avulsions were treated nonoperatively. Using a Telos device, the authors measured medial joint opening at 0° and 30° of knee flexion under 0 N and 150 N of valgus load. They found no statistically significant differences between the 2 groups on ultrasound examinations on the same knee could result in an increase in medial tibiofemoral distance of 0.4 mm and 0.4 mm at 0° and 20° of knee flexion, respectively. Future studies are recommended to understand the significance of our findings in determining the severity of a medial knee injury and the outcomes of its treatment.

Limitations
This study has a few limitations that should be considered. First, due to plastic deformation, multiple examinations on the same knee could result in increased joint laxity from the first to the final state of evaluation. Second, the 2 divisions of the superficial MCL, as well as the meniscofemoral and meniscotibial...
portions of the deep MCL, were not included in the sequence of ligament transection. As a result, some primary and secondary stabilization roles for the subdivisions of the superficial and deep MCL may not have been accounted for in our testing sequences. Finally, data on previous knee injury and symptoms were unavailable despite the fact that each specimen was examined for previous trauma and arthritic changes.

Conclusions

Dynamic ultrasonographic assessment can accurately quantify the severity of medial knee ligament injury based on medial compartment gapping. In our study, we found medial tibiofemoral distance >13.8 mm at 20° knee flexion under valgus force indicates presence of deep MCL injury with a diagnostic accuracy of 0.97.

References

1. DeLong JM, Waterman BR. Surgical techniques for the reconstruction of medial collateral ligament and posteromedial corner injuries of the knee: A systematic review. Arthroscopy 2015;31:2258-22572.e1.
2. Memarzadeh A, Melton JT. Medial collateral ligament of the knee: Anatomy, management and surgical techniques for reconstruction. Orthop Trauma 2019;33:91-99.
3. Zhu J, Dong J, Marshall B, Linde MA, Smolinski P, Fu FH. Medial collateral ligament reconstruction is necessary to restore anterior stability with anterior cruciate and medial collateral ligament injury. Knee Surg Sports Traumatol Arthrosc 2018;26:550-557.
4. Madi S, Acharya K, Pandey V. Current concepts on management of medial and posteromedial knee injuries. J Clin Orthop Trauma 2022;27:101807.
5. Robinson JR, Bull AM, Thomas RR, Amis AA. The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity. Am J Sports Med 2006;34:1815-1823.
6. Jokela MA, Mäkinen TJ, Koivikko MP, Lindahl JM, Halinen J, Lindahl J. Treatment of medial-sided injuries in patients with early bicruciate ligament reconstruction for knee dislocation. Knee Surg Sports Traumatol Arthrosc 2021;29:1872-1879.
7. Giannotti BF, Rudy T, Graziano J. The non-surgical management of isolated medial collateral ligament injuries of the knee. Sports Med Arthrosc Rev 2006;14:74-77.
8. Vosoughi F, Rezaei Dogahre R, Nuri A, Ayati Firoozabadi M, Mortazavi J. Medial collateral ligament injury of the knee: A review on current concept and management. Arch Bone Joint Surg 2021;9:255-262.
9. D’Ambrosi R, Corona K, Guerra G, Cerciello S, Ursino N, Cavaignac E, et al. Midterm outcomes, complications, and return to sports after medial collateral ligament and posterior oblique ligament reconstruction for medial knee instability: A systematic review. Orthop J Sports Med 2021;9:23259671211056070.
10. Tapasvi S, Shekhar A, Patil S, Getgood A. Anatomic medial knee reconstruction restores stability and function at minimum 2 years follow-up. Knee Surg Sports Traumatol Arthrosc 2022;30:280-287.
11. Zalfagnini S, Bignozzi S, Martelli S, Lopomo N, Maracci M. Does ACL reconstruction restore knee stability in combined lesions? An in vivo study. Clin Orthop Relat Res 2007;454:95-99.
12. Guenther D, Pfeiffer T, Petersen W, et al. Treatment of combined injuries to the ACL and the MCL complex: A consensus statement of the Ligament Injury Committee of the German Knee Society (DKG). Orthop J Sports Med 2021;9:23259671211050929.
13. Fetto JF, Marshall JL. Medial collateral ligament injuries of the knee: A rationale for treatment. Clin Orthop Relat Res 1978;(132):206-218.
14. Rachun A. Committee on the Medical Aspects of Sports Committee on the Medical Aspects of Sports Subcommittee on Classification of Sports Injuries. Standard nomenclature of athletic injuries 1968. Chicago, IL: American Medical Association.
15. Meyer P, Reiter A, Akoto R, et al. Imaging of the medial collateral ligament of the knee: A systematic review [published online October 20, 2021]. Arch Orthop Trauma Surg. doi:10.1007/s00402-021-04200-8
16. LaPrade RF, Bernhardson AS, Griffith CJ, Macalena JA, Wijdicks CA. Correlation of valgus stress radiographs with medial knee ligament injuries: An in vitro biomechanical study. Am J Sports Med 2010;38:330-338.
17. Ghosh N, Kruse D, Subeh M, Lahham S, Fox JC. Comparing Point-of-care-ultrasound (POCUS) to MRI for the diagnosis of medial compartment knee injuries. J Med Ultrasound 2017:25:167-172.
18. Lutz PM, Höher LS, Feucht MJ, Neumann J, Junker D, Wörtler K, et al. Ultrasound-based evaluation revealed reliable postoperative knee stability after combined acute ACL and MCL injuries. J Exp Orthop 2021;8:76.
19. Lutz PM, Feucht MJ, Wechselberger J, et al. Ultrasound-based examination of the medial ligament complex shows gender- and age-related differences in laxity. Knee Surg Sports Traumatol Arthrosc 2021;29:1960-1967.
20. Kleinbaum Y, Blankstein A. Mild to moderate medial collateral ligament (MCL) injuries of the knee: Sonographic findings and sonographic valgus stress test. J Musculoskelet Res 2008;11:9-14.
21. Wijdicks CA, Ewart DT, Nuckley DJ, Johansen S, Engebretsen L, Laprade RF. Structural properties of the primary medial knee ligaments. Am J Sports Med 2010;38:1638-1646.
22. Lemeshow S, Sturdivant RX, Hosmer DW Jr. Applied logistic regression. New York: John Wiley & Sons, 2013.
23. Cohen J. Statistical power analysis for the behavioral sciences. Routledge, 2013.
24. Shrout PE, Fleiss JL. Intraclass correlations: Uses in assessing rater reliability. Psychol Bull 1979;86:420.
25. Slane LC, Slane JA, Scheys L. The measurement of medial knee gap width using ultrasound. Arch Orthop Trauma Surg 2017;137:1121-1128.
26. Whelan D, Leiter J, Sasyniuk T, et al. Double-row repair of the distal attachment of the superficial medial collateral ligament: A basic science pilot study. *Knee Surg Sports Traumatol Arthrosc* 2015;23:2820-2824.

27. Dong J, Wang XF, Men X, Zhu J, Walker GN, Zheng XZ, et al. Surgical treatment of acute grade iii medial collateral ligament injury combined with anterior cruciate ligament injury: Anatomic ligament repair versus triangular ligament reconstruction. *Arthroscopy* 2015;31:1108-1116.

28. Abermann E, Wierer G, Herfort M, Smigielski R, Fink C. MCL Reconstruction using a flat tendon graft for anteromedial and posteromedial instability. *Arthrosc Tech* 2022;11:e291-e300.
**Appendix Table 1.** Differences in Area Under ROC Curves (AUC) of Medial Tibiofemoral Distance Based on Ultrasonographic and Fluoroscopic Evaluation for Each Successive Injury State

| Force                  | AUC for Ultrasound | 95% CI | AUC for Fluoroscopy | 95% CI  | Difference in AUC | P Value |
|------------------------|--------------------|--------|---------------------|---------|-------------------|---------|
| Stage 0 vs stage 1     | 0.98               | 0.77-1.0 | 0.96                | 0.88-1.0 | 0.01              | .737    |
| Stage 1 vs stage 2     | 0.89               | 0.64-0.99 | 0.97                | 0.74-1.0 | 0.1               | .207    |
| Stage 2 vs stage 3     | 0.88               | 0.63-0.99 | 0.90                | 0.71-1.0 | 0.02              | .829    |
| Stage 3 vs stage 4     | 0.84               | 0.58-0.97 | 0.86                | 0.65-0.99 | 0.02              | .848    |
| Stable vs unstable     | 0.97               | 0.82-1.00 | 0.98                | 0.83-1.0 | 0.01              | .220    |

ACL, anterior cruciate ligament; AUC, area under the curve; CI, confidence interval; dMCL, deep medial collateral ligament; %, percentage; POL, posterior oblique ligament; sMCL, superficial medial collateral ligament; stable injuries, combined stage 0 and stage 1; stage 0, intact state; stage 1, transectioning of sMCL; stage 2, transectioning of sMCL and dMCL; stage 3 transectioning of sMCL, dMCL, and POL; stage 4, transectioning of sMCL, dMCL, POL, and ACL; unstable injuries, stage 2.