Original Article

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

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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 .049 to <.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,[4,6-8] reconstruction is indicated in cases of persistent grade 3 medial knee laxity.[1,9,10] Inadequately treated medial knee injures 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.

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The authors report the following potential conflicts of interest or sources of funding: B.L. and C.W.D. declare nonfinancial research support from Arthrex and Butterfly Network at the time of the study. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

This study was accepted as a poster presentation for the AANA 2022 Annual Meeting, May 19 to 21, 2022, San Francisco, California.

Received April 27, 2022; accepted July 2, 2022.

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2666-061X/22568

https://doi.org/10.1016/j.asmr.2022.07.003

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 gapping 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 force[21] (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

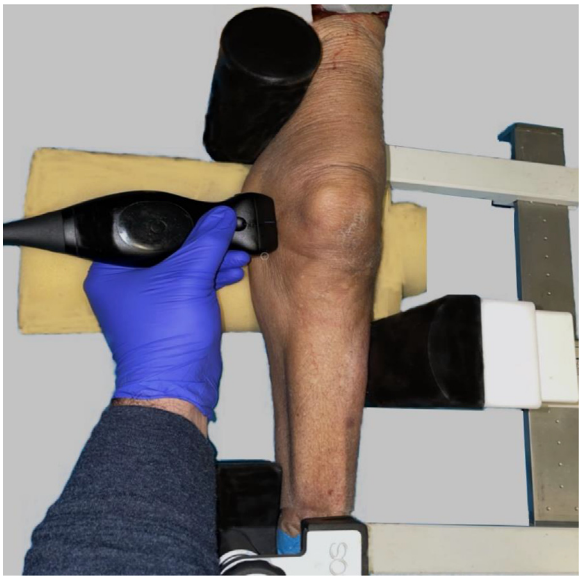

Fig 1. The experimental setup demonstrates a left knee mounted in a Telos device, which was used to perform valgus stress tests under 100 N force at 0° and 20° of knee flexion. The portable ultrasound probe is positioned perpendicular to the medial joint line over the medial collateral ligament.

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 distance between the articular margins of the medial femoral condyle and the 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

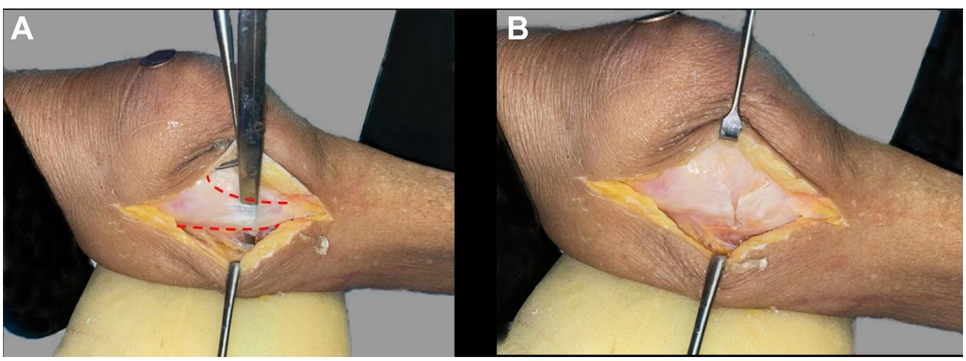

Fig 2. (A) Medial view of the left knee with superficial medial collateral ligament identified and isolated. (B) The superficial medial collateral ligament is transected.

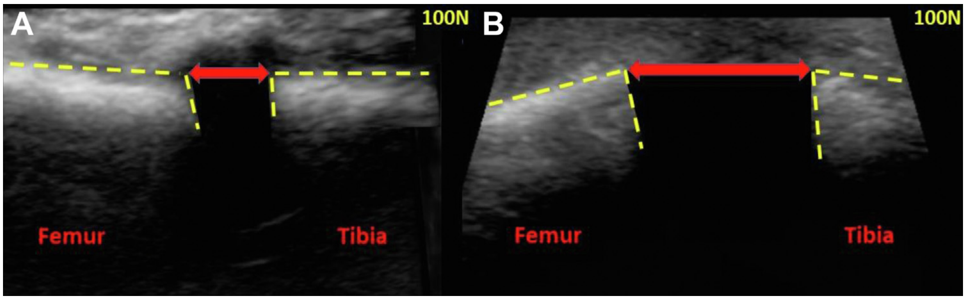

Fig 3. Ultrasound images of the medial compartment of the left knee taken at 20° of flexion with a portable ultrasound probe positioned perpendicular to the medial joint line over the medial collateral ligament. The medial tibiofemoral distance was calculated by measuring the distance between the articular margins (indicated by dashed yellow lines) of the medial femoral condyle and the medial tibial plateau. (A) Ultrasound image demonstrating medial tibiofemoral distance under 100 N of valgus force in an intact knee. (B) Ultrasound image demonstrating increased medial tibiofemoral distance under 100 N of valgus directed force after transection of the deep medial collateral ligament and posterior oblique ligament.

(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 ultrasonography 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.[22] 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).[23] 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

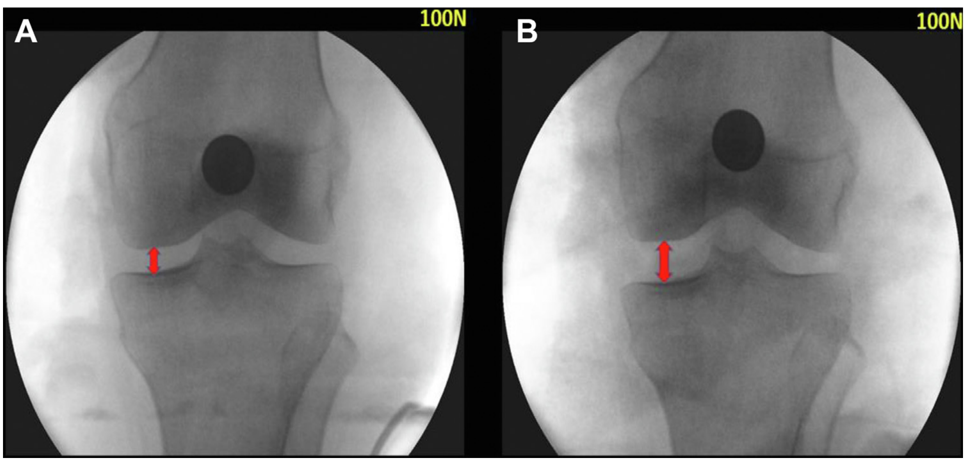

Fig 4. Fluoroscopic anteroposterior images of the left knee taken at 20° of knee flexion. The medial tibiofemoral distance was calculated by measuring the smallest perpendicular distance between the central aspect of the medial femoral condyle and the corresponding medial tibial plateau. (A) Fluoroscopic image demonstrating medial tibiofemoral distance under 100 N of valgus force in an intact knee. (B) Fluoroscopic image demonstrating increased medial tibiofemoral distance under 100 N of valgus directed force after transection of the deep medial collateral ligament and posterior oblique ligament.

Table 1. Medial Tibiofemoral Distance Based on Ultrasonographic Evaluation Comparing Intact State With Subsequent Transection

	0° Knee Flexion						20° Knee Flexion					
	Unloaded			Loaded (100 N)			Unloaded			Loaded (100 N)		
Stage	Mean ± SD, mm	Difference Compared With Intact State, mm	% Change Compared With Intact State	Mean ± SD, mm	Difference Compared With Intact State, mm	% Change Compared With Intact State, mm	Mean ± SD, mm	Difference Compared With Intact State, Mm	% Change Compared With Intact State, %	Mean ± SD, mm	Difference Compared With Intact State, mm	% change Compared With Intact State, %
Intact	6.5 ± 1.1	–	–	6.9 ± 1.1	–	–	6.6 ± 1.2	–	–	7.0 ± 1.1	–	–
sMCL	7.3 ± 1.5	0.8	12.3	10.8 ± 2.4*	3.9	56.5	8.2 ± 2.0	1.6	24.2	10.9 ± 1.8*	3.9	55.7
dMCL	10.7 ± 2.2*	4.2	64.6	14.8 ± 3.2*	7.9	114.5	11.3 ± 2.4*	6.4	97	15.7 ± 2.4*	8.7	124.3
POL	11.9 ± 2.3	5.4	83.1	15.6 ± 3.6	8.7	126.1	14.4 ± 1.9	7.8	118.2	18.6 ± 3.5*	11.6	165.7
ACL	14.1 ± 2.5	7.6	116.9	20.3 ± 2.7*	13.4	194.2	16.3 ± 2.0	9.7	146.9	22.8 ± 3.3*	15.8	225.7

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.

5 knees. To assess inter-rater reliability, each measurement was performed on 5 knee specimens by 2 observers (fellowship-trained sports medicine surgeon and fellowship-trained arthroplasty surgeon). Interpretation of the ICC values was as follows: ICC <0.4, poor; 0.4-0.59, acceptable; 0.6-0.79, good; and ICC >0.8, excellent.[24]

Results

Eight cadaveric knees were included in this study, of which 3 were male and 5 were female. The mean cadaveric age was 58 ± 11 years (range 48-82 years). The medial tibiofemoral distance increased with the severity of the medial knee injury, with the greatest distance of 22.8 mm observed on stress ultrasound at 20° of knee flexion under valgus load when all medial ligaments and ACL were transected ($P < .001$). The results are summarized in Table 1.

Ultrasound and Fluoroscopic Measurements

On ultrasonographic evaluation, the medial tibiofemoral distance in the intact state was 6.9 ± 1.1 mm and 7.0 ± 1.1 mm at 0° and 20° of knee flexion, respectively, when subjected to 100 N of valgus force (Table 1). Under a 100-N load, complete medial knee injury with additional ACL sectioning resulted in an increase in medial tibiofemoral distance to 20.3 ± 2.7 mm and 22.8 ± 3.3 mm on stress ultrasound at 0° and 20° of knee flexion, when compared with the intact state ($P < .001$).

On fluoroscopic evaluation, the medial tibiofemoral distance in the intact state was 6.2 ± 0.3 mm and 6.9 ± 0.7 mm at 0° and 20° of knee flexion, respectively, when subjected to 100 N of valgus force. The results are summarized in Table 2. Under a 100-N load, complete medial knee injury with additional ACL sectioning resulted in an increase in medial tibiofemoral distance to 15.3 ± 1.8 mm and 17.5 ± 2.2 mm on stress fluoroscopy, when compared to the intact state ($P < .001$).

Under 100 N of valgus force, a high correlation was found between the fluoroscopic and ultrasound measurements at 0° of knee flexion ($r = 0.88$, $r^2 = 0.774$, $P < .001$). Moreover, a very high correlation was found between the fluoroscopic and ultrasound measurements at 20° of knee flexion under valgus stress ($r = 0.95$, $r^2 = 0.902$, $P < .001$; Fig 5).

Accuracy of Ultrasound and Fluoroscopic Measurements to Detect Medial Knee Injury

ROC curve analyses for ultrasound measurements revealed that the AUCs to differentiate between successive severity of MCL injury had a score ranging from 0.88 to 0.98, indicating excellent to outstanding tests. Results are summarized in Table 3. Furthermore, ROC curve analyses for fluoroscopic measurements revealed that the AUCs to differentiate between successive

Table 2. Medial Tibiofemoral Distance Based on Fluoroscopic Evaluation Comparing Intact State With Subsequent Transection

	0° Knee Flexion						20° Knee Flexion					
	Unloaded			Loaded (100 N)			Unloaded			Loaded (100 N)		
Stage	Mean ± SD, mm	Difference Compared With Intact State, mm	% Change Compared With Intact State	Mean ± SD, mm	Difference Compared With Intact State, mm	% Change Compared With Intact State	Mean ± SD, mm	Difference Compared With Intact State, mm	% Change Compared With Intact State	Mean ± SD, mm	Difference Compared With Intact State, mm	% Change Compared With Intact State
Intact	5.7 ± 0.3	–	–	6.2 ± 0.3	–	–	6.1 ± 0.6	–	–	6.9 ± 0.7	–	–
sMCL	6.2 ± 0.4	0.5	8.8	8.3 ± 0.9*	2.1	33.9	6.6 ± 0.6	0.5	8.2	9.2 ± 1.3*	2.3	33.3
dMCL	8.1 ± 1.0*	2.4	42.1	10.4 ± 1.6*	4.2	50.6	8.9 ± 1.0*	2.8	45.9	12.2 ± 1.4*	5.3	76.8
POL	8.9 ± 1.5	3.2	56.1	11.8 ± 1.8	5.6	90.3	10.4 ± 2.1	4.3	70.5	14.6 ± 1.7*	7.7	111.6
ACL	10.3 ± 2.0	4.6	80.7	15.3 ± 1.8*	9.1	146.8	11.6 ± 2.1	5.5	90.2	17.5 ± 2.2*	10.6	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.

severity of MCL injury had scores ranging from 0.86 to 0.98, indicating excellent to outstanding tests. Results are summarized in Table 4. Moreover, the AUC for measurements performed using ultrasonography showed no difference from the AUC for those performed using fluoroscopy (*P* values ranging from .207 to .848; Appendix Table 1, available at www.arthroscopyjournal.org).

The ICCs for intra- and inter-rater reliability for ultrasound measurements were 0.98 (95% confidence interval 0.97-0.99) and 0.93 (95% confidence interval 0.87-0.98) respectively, indicating substantial agreement among observers.

Discussion

The most important finding of this study was that measuring the medial tibiofemoral distance with a portable ultrasound machine can accurately quantify the severity of a medial knee injury. The medial tibiofemoral distance increased from 7.0 ± 1.1 mm in an intact state to 10.9 ± 1.8 mm in an sMCL-deficient state and 15.7 ± 2.4 mm in an sMCL- and dMCL-deficient state when using 100-N valgus stress force at 20° of knee flexion. Furthermore, AUC analysis demonstrated there was equal diagnostic ability between the ultrasound technique and the previously established method of radiographic measurements.

Stress radiographs are a common imaging modality in the evaluation of MCL injuries. In a previous study, LaPrade et al.[16] evaluated the role of stress radiographs in determining the severity of medial knee injury. In 18 cadaveric knees, the authors used a 10-Nm valgus load at 0° and 20° of knee flexion in intact knees and after subsequent sectioning of the sMCL proximally and distally, the meniscofemoral and meniscotibial portions of the dMCL, the POL, and the cruciate ligaments. They reported that the medial tibiofemoral distance increased from 6.4 ± 1.0 mm in intact knees to 9.1 ± 1.2 mm after transectioning of the distal sMCL. Further sectioning of the meniscotibial ligament increased the medial tibiofemoral gap to 11.5 ± 2.4 mm at 20° of knee flexion under a valgus load of 10 Nm. Similarly, in our study, the medial tibiofemoral distance on stress radiographs in intact knees was 6.9 ± 0.7 mm under a valgus force of 100 N at 20° of knee flexion. This distance increased to 9.2 ± 1.3 mm and 12.2 ± 1.4 mm in isolated sMCL and in combined sMCL and dMCL injury, respectively. In addition, we also found that the cut-off value to detect sMCL injury on radiographs was 7.6 mm (AUC = 0.96, sensitivity = 100%, and specificity = 87.5%) and 10.9 mm (AUC = 0.97, sensitivity = 87.5%, and specificity = 100%) for combined sMCL and dMCL injury, respectively. Moreover, we found a strong positive correlation between the fluoroscopic and ultrasound measurements at 20° of knee flexion under valgus stress (r = 0.95) and the AUC

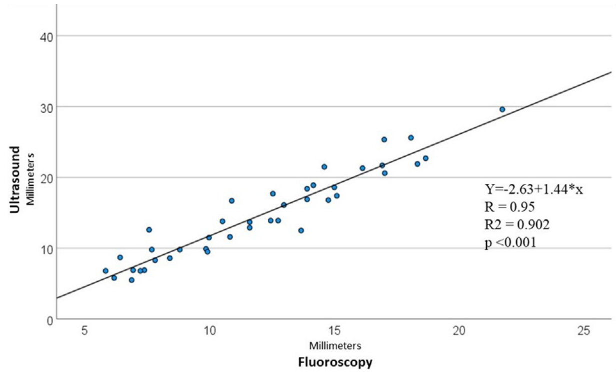

Fig 5. Scatter plot demonstrates a very high correlation between ultrasound and fluoroscopy in detecting medial knee injury at 20° of flexion with a valgus load of 100 N.

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 mimick 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

Medial Tibiofemoral Distance at 20° of Knee Flexion Under Valgus 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 injuries	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, 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.

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 dMCL 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 gapping, as improvements in technique have been linked to better results.[9,26-28] Lutz et al.[18] 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, with difference between loaded and unloaded states of 2.3 ± 1.2 mm and 2.3 ± 1.3 mm at 0° and 30° of knee flexion, respectively, in group 1, and 2.1 ± 0.7 mm and 2.1 ± 1.1 mm at 0° and 30° of knee flexion, respectively in group 2. In our study, the difference between measurements performed under a valgus directed force of 0 and 100 N in intact knees resulted 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.

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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

Medial Tibiofemoral Distance at 20° of Knee Flexion Under Valgus 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 injuries	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.