Correlation of Valgus Stress Radiographs With Medial Knee Ligament Injuries

An In Vitro Biomechanical Study

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Background: The amount of medial compartment opening for medial knee injuries determined by valgus stress radiography has not been well documented. The purpose of this study was to develop clinical guidelines for diagnosing medial knee injuries using valgus stress radiography.

Hypothesis: Measurements of medial compartment gapping can accurately differentiate between normal and injured medial structure knees on valgus stress radiographs.

Study Design: Controlled laboratory study.

Methods: Valgus stress radiographs were obtained on 18 adult lower extremities using 10-N·m and clinician-applied valgus loads at 0° and 20° of flexion to intact knees and after sequential sectioning of the superficial medial collateral ligament proximally and distally, the meniscofemoral and meniscotibial portions of the deep medial collateral ligament, the posterior oblique ligament, and the cruciate ligaments. Three independent observers of different experience levels measured all of the radiographs during 2 separate occasions to determine intraobserver repeatability and interobserver reproducibility.

Results: Compared with the intact knee, significant medial joint gapping increases of 1.7 mm and 3.2 mm were produced at 0° and 20° of flexion, respectively, by a clinician-applied load on an isolated grade III superficial medial collateral ligament simulated injury. A complete medial knee injury yielded gapping increases of 6.5 mm and 9.8 mm at 0° and 20°, respectively, for a clinician-applied load. Intraobserver repeatability and interobserver reproducibility intraclass correlation coefficients were .99 and .98, respectively.

Conclusion: Valgus stress radiographs accurately and reliably measure medial compartment gapping but cannot definitively differentiate between meniscofemoral- and meniscotibial-based injuries. A grade III medial collateral ligament injury should be suspected with greater than 3.2 mm of medial compartment gapping compared to the contralateral knee at 20° of flexion, and this injury will also result in gapping in full extension.

Clinical Significance: Valgus stress radiographs provide objective and reproducible measurements of medial compartment gapping, which should prove useful for definitive diagnosis, management, and postoperative follow-up of patients with medial knee injuries.

Keywords: medial collateral ligament; posterior oblique ligament; valgus stress radiographs; medial knee injuries

The medial collateral ligament and medial knee stabilizers are the most commonly injured structures of the knee.[11,15,35,45] Early diagnosis is crucial for both identification of the injury grade and for treatment planning for both isolated medial knee ligament injuries and those medial knee injuries with concurrent cruciate ligament injuries.[5,8,19,20,26,34,38,39,43,49] Physical examination is the initial method of choice for the diagnosis of medial knee injuries through the application of a valgus load in both full extension and at 20° to 30° of knee flexion.[12,14] The grading of medial knee ligament injuries by physical examination relies on both the patient's ability to relax and also the clinician's ability to detect an end point during the

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application of the valgus load at 30° of knee flexion. In addition, the presence of concurrent injuries can obscure the physical examination.[36] This reliance on a qualitative physical examination allows for potential subjective error in the diagnosis and grading of the injury, especially in the presence of combined ligament injuries.[11,25,35] Other diagnostic options for evaluation of medial knee injuries exist including magnetic resonance imaging and valgus stress radiographs.[31,37,40] By performing valgus stress radiographs, a comparison with the unaffected contralateral knee can be used to judge the degree of instability, indicated by the amount of medial compartment gapping, and allow for more objective grading of the injury.[21-23,40,44] Moreover, treatment efficacy can be assessed by monitoring the gapping change after either nonoperative or operative interventions.[11,19,23,43] Therefore, valgus stress radiographs could be used not only to diagnose medial knee injuries but also as a potentially reliable and quantitative indicator for the return of stability throughout treatment.

The medial knee anatomy literature has described a proximal and distal division of the superficial medial collateral ligament (sMCL), meniscofemoral and meniscotibial divisions of the deep medial collateral ligament (MCL), and the capsular arm of the posterior oblique ligament (POL) as the main medial knee structures.[15,28] Recent studies have described the individual biomechanical functions of these divisions and structures as well as the load-sharing relationships between these structures.[9,10,48] Because of the complex biomechanical interactions between medial knee structures, it is important to develop examination techniques that accurately identify the injured components.

Previous studies have compared the amount of medial compartment gapping on bilateral valgus stress radiographs in normal subjects and have reported there is minimal physiological side-to-side variance between knees for valgus rotation.[22,23,44] While several biomechanical studies have compared medial compartment opening in intact versus sectioned knees with various valgus loads applied,[11,12,21-23,32,33,41,46,50] none of these studies have radiographically quantified the amount of medial compartment gapping from the tibial plateau to the femoral subchondral surfaces in discrete linear distances for specific medial knee injuries. Further, none of the previous radiographic studies differentiated between injuries to the proximal and distal divisions of the sMCL or the meniscofemoral and meniscotibial divisions of the deep MCL.[11,32,50]

To our knowledge, clear radiographic measurement guidelines, which assist in the identification of grade III medial knee injuries or monitor improvement after treatment, have not been developed. Thus, our hypothesis was that when compared with the intact state, a sufficiently reproducible amount of medial joint space gapping occurs between grade III isolated and combined medial knee injury patterns to permit identification of and differentiation between these injury patterns radiographically. The purpose of this study was to quantitate the amount of medial compartment gapping seen with medial knee injuries to augment current noninvasive methods for identifying and grading the severity of medial knee injuries, which will empower clinicians to be more confident and accurate in treatment recommendations.

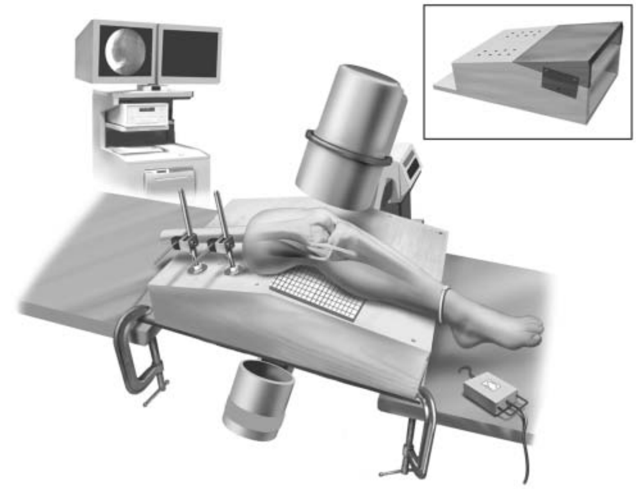

Figure 1. Illustration depicting a medial view of the valgus stress testing set-up, with a left knee flexed at 20° on the jig, and the C-arm fluoroscopy machine with imaging monitors and the force device attached (inset demonstrating wedge insert to allow for knees to be stressed in full extension).

MATERIALS AND METHODS

Specimen Preparation

Eighteen fresh-frozen, three-quarter lower extremities (mean age, 75.6 years; range, 66-86 years), without evidence of surgical scars or instability on clinical examination, were used in this study. In addition, knees with osteoarthritis as determined by fluoroscopic images or on examination were excluded.[41] Specimens were kept frozen at −20°C and thawed at room temperature before testing. In preparation for testing, the skin and subcutaneous fat were removed to allow for identification of structures, leaving the investing fascia intact. All soft tissues were removed approximately 15 cm proximal to the knee to expose the femur. Two 4-mm-diameter tunnels were then drilled from lateral to medial through the exposed femur for static fixation of the specimens to the testing apparatus (Figure 1), with 5 cm separating the 2 tunnels. The proximal and distal divisions of the sMCL, POL, and the meniscofemoral and meniscotibial portions of the deep MCL[28] were dissected out and tagged with sutures for later identification during testing. The anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) were accessed via a mini-parapatellar arthrotomy incision, which was closed with sutures before testing. Posttesting dissection was performed to verify that all structures had been completely sectioned.

Biomechanical Testing

The femur was secured using two 6-mm Schantz pins to a 20° fixed-angle radiolucent jig with the joint line at the apex (Figure 1). According to the International Knee Documentation Committee (IKDC) objective guidelines for medial compartment opening, 20° of knee flexion was used for stress testing.[2,13] A second test condition at 0° of flexion was also used to compare with previous studies that have investigated medial joint line gapping to valgus loads applied in full extension.[8,18,32,35,39] A custom removable radiolucent wedge, with a blocking piece, was secured to the jig under the lower leg to achieve the 0° knee flexion position. The distal portion of the leg was allowed to glide freely in both the medial or lateral direction. A radio-opaque 1 cm × 1 cm grid was placed directly under the proximal portion of the tibia at the joint line to serve as a magnification correction guide. True anterior-posterior (AP) radiographs perpendicular to the joint line[29] were obtained at 0° and 20° of knee flexion (Figure 2) using a fluoroscopy C-arm (MiniView 6800 Mobile imaging system, GE Healthcare, Milwaukee, Wisconsin). The specimens were tested in the intact state and after sequential structure sectioning based on 2 differing protocols (Table 1)[35,47] to ultimately involve the complete sectioning of the main medial knee structures and cruciate ligaments. For each separate sectioning sequence, we first created either a complete femoral (meniscofemoral-based) (protocol A) or tibial (meniscotibial-based) (protocol B) medial knee injury to allow for assessment of reported potential differences in medial compartment gapping between these 2 injury locations. The determination of which medial knee structures to section and the sequence of individual structure sectioning in our study were determined based on our clinical experience and a study of the available literature.[9,10,28,48] The 2 sequential sectioning protocols (with 8 cut states), 2 different flexion angles, and 2 different applied loads resulted in a total of 32 unique test conditions including the intact state for each knee. Based on previous valgus stress load studies,[44] a 10-N·m valgus load was applied perpendicular to the tibia using a model SM S-type Load Cell with an attached handle (Interface, Scottsdale, Arizona), with a manufacturer-reported nonrepeatability error of ±0.01%. Pilot studies involving 15-N·m and 20-N·m forces produced premature medial structure failure of the specimens, rendering them unusable for further sectioning states. The clinician-applied valgus load simulated a clinical examination by applying one hand on the thigh above the knee, and the opposing hand was placed around the ankle at the medial malleolus to apply the valgus load. All clinical loads were applied to the knees by the same examiner. The testing conditions were repeated 3 times each, with one image taken each time, resulting in a total of up to 96 images per knee.

Data Analysis

The knee images were stored and accessed through our institution's picture archiving and communication system (PACS). Using the PACS measuring tool, the closest perpendicular distance between the central aspect of the medial femoral condyle and the corresponding medial tibial plateau was used for measurement. "Gapping" was defined as the shortest distance between the subchondral bone surface of the most distal aspect of the medial femoral condyle and the corresponding medial tibial plateau without taking into account the thickness of the articular cartilage. The placement of the 1 cm × 1 cm grid in the image was used to calibrate the images to account for magnification differences between radiographs.

The IKDC objective evaluation form for knee injuries[2,13] was also used to grade the different injury states. The present study reported the grade of the simulated injury as per the guidelines of the 2000 IKDC objective knee examination grading form for the amount of medial compartment gapping seen by stress radiographs with medial knee structure sectioning at 20° of knee flexion. Grades assigned were A (0-2 mm: normal), B (3-5 mm:

Figure 2. Fluoroscopic image made after medial structure sectioning under applied valgus load and an example of the measurement in millimeters of medial compartment gapping (left knee, 20° of knee flexion). The 50-mm measurement is the calibration line projected along 5 cm of the calibration grid.

TABLE 1
Sequential Sectioning Groups[a]

Group	Cutting Sequence
A	Intact → Proximal sMCL → MF → POL → Distal sMCL → MT → ACL → PCL
B	Intact → Distal sMCL → MT → Proximal sMCL → MF → POL → PCL → ACL

[a]sMCL, superficial medial collateral ligament; MF, meniscofemoral attachment of deep medial collateral ligament; POL, posterior oblique ligament; MT, meniscotibial attachment of deep medial collateral ligament; ACL, anterior cruciate ligament; PCL, posterior cruciate ligament. Arrow indicates that a cut was made.

TABLE 2
Average Gapping Increase Compared With Intact Knee[a]

Flexion Angle / Applied Load	0° 10 N·m	0° Clinician	20° 10 N·m	20° Clinician
	Medial Joint Line Gapping (mm ± standard deviation)			
Protocol A				
Intact	6.9 ± 0.8	7.9 ± 0.7	6.4 ± 0.9	7.4 ± 0.7
Proximal sMCL	8.6 ± 1.0[b]	9.4 ± 1.0[b]	9.2 ± 1.8[b]	10.6 ± 1.9[b]
MF	9.2 ± 1.1	9.9 ± 1.2	10.8 ± 1.9[b]	12.2 ± 2.0[b]
POL	11.3 ± 1.7[b]	12.2 ± 1.5[b]	13.2 ± 1.6[b]	14.1 ± 2.1[b]
Distal sMCL	12.4 ± 2.0[b]	13.2 ± 2.6	13.9 ± 2.1	15.3 ± 2.3[b]
MT	12.6 ± 2.2	14.1 ± 2.8	15.2 ± 2.1[b]	16.2 ± 2.8
ACL	13.9 ± 2.9[b]	15.9 ± 3.9[b]	18.2 ± 2.7[b]	21.2 ± 3.9[b]
PCL	–	21.6 ± 4.2[b]	22.2 ± 3.3[b]	27.8 ± 4.7[b]
Protocol B				
Intact	6.6 ± 1.1	7.5 ± 1.2	6.4 ± 1.0	7.5 ± 1.0
Distal sMCL	8.4 ± 1.0[b]	9.5 ± 1.3[b]	9.1 ± 1.2[b]	10.6 ± 1.4[b]
MT	10.0 ± 1.5[b]	11.1 ± 1.9[b]	11.5 ± 2.4[b]	12.9 ± 2.2[b]
Proximal sMCL	10.4 ± 1.6	11.6 ± 1.9	12.4 ± 2.6[b]	13.9 ± 2.6[b]
MF	11.2 ± 1.8	12.3 ± 2.0	13.3 ± 2.6[b]	15.3 ± 2.8[b]
POL	12.4 ± 2.2	14.3 ± 2.8[b]	14.8 ± 2.5[b]	17.3 ± 3.4[b]
PCL	16.1 ± 3.5[b]	19.3 ± 3.1[b]	17.3 ± 3.6[b]	20.1 ± 4.5[b]
ACL	22.9 ± 3.9[b]	20.3 ± 2.3[b]	19.6 ± 3.1[b]	23.0 ± 4.1[b]

[a]sMCL, superficial medial collateral ligament; MT, meniscotibial; MF, meniscofemoral; POL, posterior oblique ligament; PCL, posterior cruciate ligament; ACL, anterior cruciate ligament.
[b]Significant change compared with the previous sectioned state.

near normal), C (6-10 mm: abnormal), or D (>10 mm: grossly abnormal).

Intraobserver Repeatability and Interobserver Reproducibility

Intraobserver repeatability was measured by having 3 examiners measure the amount of medial compartment gapping on each set of radiographs twice, with trials being a minimum of 2 weeks apart to prevent recall bias. Interobserver reproducibility was measured by having examiners with different levels of training independently measure the valgus stress radiographs for each knee. The observers were a medical student, an orthopaedic surgery chief resident, and an orthopaedic sports medicine faculty member.

Statistical Methods

SAS software (SAS 9.1.3 for Windows, SAS Institute, Cary, North Carolina) was used to analyze the variance in repeated measures mixed models for the load, knee state, observer, and trial means for differences. For each unique combination of sectioning sequence (protocol A and protocol B), flexion angle (0° and 20°), and applied load (10 N·m or clinician), we performed a 2-way analysis of variance for the model log10(Gap) = Specimen × Cut State, using the GLM procedure in SAS. A log transform of Gap was used because the raw distribution was skewed to the right. We compared the means of the cut states pairwise using a Tukey adjustment to the P values (Tukey honest significant difference). A P value <.05 was considered significant. To examine if there were differences in medial compartment gapping at 0° and 20° between both the complete meniscofemoral-based and meniscotibial-based medial knee injury states and also for the ACL- versus PCL-sectioned states after all medial knee structures were sectioned, we compared the means of (1) a complete meniscofemoral-based to a meniscotibial-based medial knee injury and (2) a complete medial knee injury and the means of sectioning either the PCL or ACL by using 2-sample t tests and a rank-sum test.

RESULTS

All biomechanical data are summarized in Tables 2 and 3 for both 0° and 20° flexion angles, respectively. The results for the intact and all tested structures sectioned states were averaged between the 2 testing protocols. Statistically significant values are noted compared with the previous test state. A brief overview of the main clinically relevant sectioned states follows.

Protocol A

Compared with the intact state, sectioning of the proximal sMCL produced an increase of 1.7 mm ($P < .001$) and 2.8 mm ($P < .001$) of medial compartment gapping at 0° and 20° flexion, respectively, for the 10-N·m load. The clinician-applied valgus load generated an increase of 1.5 mm ($P < .001$) and 3.2 mm ($P < .001$) of medial compartment gapping for 0° and 20° of flexion, respectively.

TABLE 3
Correlation of International Knee Documentation Committee (IKDC) Objective Scoring System to Amount of Medial Compartment Gapping Seen With Medial Knee Structure Sectioning[a]

	IKDC Knee Injury Grade
10-N·m Load	
Protocol A	
PSMCL	Normal
PSMCL + MF	Nearly normal
PSMCL + MF + POL (complete mensicofemoral-based injury)	Abnormal
PSMCL + MF + POL + DSMCL	Abnormal
PSMCL + MF + POL + DSMCL + MT (complete medial knee injury)	Abnormal
Complete medial structure injury + ACL	Severely abnormal
Protocol B	
DSMCL	Nearly normal
DSMCL + MT (complete mensicotibial-based injury)	Abnormal
DSMCL + MT + PSMCL	Abnormal
DSMCL + MT + PSMCL + MF	Abnormal
DSMCL + MT + PSMCL + MF + POL (complete medial knee injury)	Abnormal
Complete medial knee injury + PCL	Severely abnormal
Complete medial knee injury + PCL + ACL	Severely abnormal
Clinician-Applied Load	Knee Injury Grade
Protocol A	
PSMCL	Nearly normal
PSMCL + MF	Nearly normal
PSMCL + MF + POL (complete mensicofemoral-based injury)	Abnormal
PSMCL + MF + POL + DSMCL	Abnormal
PSMCL + MF + POL + DSMCL + MT (complete medial knee injury)	Abnormal
Complete medial structure injury + ACL	Severely abnormal
Protocol B	
DSMCL	Nearly normal
DSMCL + MT (complete mensicotibial-based injury)	Abnormal
DSMCL + MT + PSMCL	Abnormal
DSMCL + MT + PSMCL + MF	Abnormal
DSMCL + MT + PSMCL + MF + POL (complete medial knee injury)	Abnormal
Complete medial knee injury + PCL	Severely abnormal
Complete medial knee injury + PCL + ACL	Severely abnormal

[a]PSMCL, proximal superficial medial collateral ligament; MF, meniscofemoral portion of deep medial collateral ligament; POL, posterior oblique ligament; DSMCL, distal tibial attachment of superficial medial collateral ligament; MT, meniscotibial ligament portion of deep medial collateral ligament; ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

Sectioning to create a complete meniscofemoral-based medial knee injury resulted in an increased gapping of 4.4 mm and 6.8 mm over the intact state when a 10-N·m load was applied at 0° and 20° flexion, respectively. For the clinician-applied valgus load, the observed gapping increase over the intact state was 4.3 mm and 6.7 mm for 0° and 20° of flexion, respectively.

Sequential sectioning to include all tested medial knee structures resulted in an increased gapping of 5.7 mm and 8.8 mm at 0° and 20° of flexion, respectively, over the intact state when a 10-N·m load was applied. The observed gapping increase compared to the intact state was 6.2 mm and 8.8 mm for the clinician-applied valgus load at 0° and 20° of flexion, respectively.

A simulated combined complete medial knee and ACL injury produced increased gapping of 7.0 mm and 11.8 mm (significant increases of 1.3 mm [$P < .001$] and 3.0 mm [$P < .001$] compared with the previous cut state) at 0° and 20° of flexion, respectively, over the intact state when a 10-N·m load was applied. A clinician-applied stress to this simulated injury resulted in increased gapping of 8.0 mm and 13.8 mm (significant increases of 1.8 mm [$P < .001$] and 5.0 mm [$P < .001$] compared with the previous cut state) at 0° and 20° of flexion, respectively, over the intact state. In knees with combined injuries to the medial knee structures and ACL (protocol A), the load application order was changed based upon our pilot data results, which found frequent specimen failure with load application at 0°. The knees were first tested at 20° of knee flexion and then finally tested at 0°. Further sectioning of the PCL increased the gapping by 4.0 mm at 20° of flexion ($P < .001$) for a 10-N·m load. For the clinician-applied load in a knee with a complete medial knee and bicruciate injury, the medial compartment gapping increased by 21.6 mm and 27.6 mm compared with the intact state (5.7 mm and 6.6 mm compared with the previous cut state) at 0° and 20° of knee flexion, respectively ($P < .001$). We were unable to assess the medial compartment gapping at 0° with an applied 10-N·m load for this simulated injury because of an inability to maintain a 10-N·m force without further structure damage for 6 of the 8 knees.

Protocol B

Sectioning of the distal division of the sMCL created significant increases in medial compartment gapping of 1.8 mm ($P < .001$) and 2.7 mm ($P < .001$) at 0° and 20° of flexion, respectively, compared with the intact state for the 10-N·m load. The clinician-applied valgus load generated a significant increase in gapping of 2.0 mm ($P < .001$) and 3.1 mm ($P < .001$) over the intact state at 0° and 20° of flexion, respectively.

Further sequential sectioning to create a complete meniscotibial-based medial knee injury increased medial compartment gapping by 3.4 mm and 5.1 mm compared with the intact state for the 10-N·m load at 0° and 20° of flexion, respectively. A clinician-applied valgus load produced increased medial compartment opening of 3.6 mm and 5.3 mm compared with the previous cut state at 0° and 20° of flexion, respectively, compared with the intact state.

Further sectioning of all tested medial knee structures increased medial compartment gapping by 5.8 mm and 8.4 mm at 0° and 20° of flexion, respectively, compared with the intact state for the 10-N·m load. Compared with the intact state, the clinician-applied valgus load created an increased gapping of 6.8 mm and 9.8 mm at 0° and 20° of flexion, respectively.

Subsequent sectioning of the PCL, in addition to the medial knee structures, resulted in increased gapping of 9.5 mm and 10.9 mm (significant increases of 3.7 mm [$P < .001$] and 2.5 mm [$P < .001$] compared with the previous cut state) at 0° and 20° of flexion, respectively, compared with the intact state using a 10-N·m load. The clinician-applied valgus load produced an increase of 11.8 mm and 12.6 mm (significant increases of 5.0 mm [$P < .001$] and 2.8 mm [$P < .001$] compared with the previous cut state) compared with the intact state at 0° and 20° of flexion, respectively. Compared with a complete medial knee and PCL injury, the loss of the ACL further increased medial compartment gapping by 16.3 mm and 13.2 mm (significant increases of 6.8 mm [$P < .001$] at 0° and 2.3 mm [$P < .001$] at 20° compared with the previous cut state) at 0° and 20° of flexion, respectively, compared with the intact state using a 10-N·m load. The clinician-applied valgus load resulted in medial compartment gapping increases of 12.8 mm and 13.2 mm (significant increases of 1.0 mm [$P < .001$] in 0° of flexion and 2.9 mm [$P < .001$] in 20° of flexion) compared with the intact state at 0° and 20° of flexion, respectively.

Comparison of Complete Meniscofemoral-based Versus Meniscotibial-based Medial Knee Sectioning

A comparison of the difference in medial compartment gapping for a complete meniscofemoral-based versus meniscotibial-based medial knee injury at 0° found a significant increase in medial compartment gapping of 1.1 mm ($P < .001$) for the 10-N·m load and 0.7 mm ($P < .03$) for the clinician-applied load for the meniscofemoral-based injury. At 20° of knee flexion, there was also a significant increase in medial compartment gapping between the meniscofemoral-based and meniscotibial-based medial knee injury of 1.5 mm ($P < .001$) for the 10-N·m load and 1.3 mm ($P < .001$) for the clinician-applied load for the meniscofemoral-based injury.

Comparison of Sectioning of Cruciate Ligaments on Increased Medial Compartment Gapping

A comparison of the difference in medial compartment gapping for ACL or PCL sectioning at 0° and 20°, after the medial knee structures were completely sectioned, found a significant increase in gapping of 3.2 mm when sectioning the PCL under a clinician-applied stress when compared with sectioning the ACL in extension ($P < .02$). We also found that at 20° of flexion with a clinician-applied load, a significant increase of 2.2 mm in medial gapping was found for ACL sectioning compared with PCL sectioning ($P < .03$).

IKDC Correlation

Correlation of the above stated medial compartment gapping due to simulated medial knee injury with the IKDC objective knee examination scoring system is reported in Table 3.

Intraobserver and Interobserver Analysis

Intraobserver intraclass correlation coefficients for each observer were .99 between trials 1 and 2. The interobserver intraclass correlation coefficients for trial 1, trial 2, and the combined trials were .98.

DISCUSSION

In our study, we found that for valgus stress radiographs, the amount of medial compartment knee gapping due to medial structure injury can be accurately and reliably measured on digital radiographs. Valgus stress radiographs provide an objective and reproducible measure of medial compartment gapping, which should prove useful for the definitive diagnosis, management, and postoperative follow-up of patients with medial knee injuries and combined medial knee and cruciate injuries. To our knowledge, this is the first study to quantitate the amount of radiographic gapping for the individual components of the medial knee structures on valgus stress radiographs.

Prior grading schemes have created ambiguity regarding a standard set of criteria for grading medial knee injuries. Previous studies cite the American Medical Association report from 1966 that defined a grading system; however, injury grades were only described in subjective terms[1] and simply stated "stress films show instability" rather than quantitatively defining the radiographic joint space opening. Based on these criteria, the widely referenced injured medial or lateral knee grading scale has been grades I to III, in which grade I represents mild opening (0-5 mm), grade II represents moderate opening (5-10 mm), and grade III represents complete opening (>10 mm).[4,17,30,35,36] However, we found that a simulated grade III sMCL injury torn off either its femoral or distal tibial attachment required only 3.2 mm of increased medial compartment gapping at 20° of knee flexion versus the intact state. Medial joint line gapping has also been expressed as a ratio of the injured knee's gapping divided by the uninjured knee's gapping.[40] However, again, exact measurements were not defined with regard to injury grade for determining physiological laxity versus instability.[40]

The IKDC objective knee examination scoring system was designed to evaluate medial knee injuries at 20° of knee flexion by assessing for increased medial compartment gapping compared to the contralateral side.[2] A correlation between our objective findings and the IKDC objective knee examination guidelines indicates that the current IKDC objective scoring guidelines may underestimate the severity of an anatomical injury because the current guidelines utilize clinician estimation of gapping to determine the grading score rather than radiographic measurement. Therefore, we suggest that both the IKDC objective grading score and the referenced American Medical Association grades need to be re-evaluated for medial compartment gapping.

It has been reported that for isolated medial knee injuries, the majority of the medial compartment gapping can be discerned at 20° to 30° of knee flexion, and valgus instability in extension occurs when one or both cruciate ligaments are concurrently injured with the medial knee structures.[17] However, we found that for both the 10-N·m and clinician-applied load, there was a significant increase in medial compartment gapping compared with the intact state for both isolated proximal or distal sMCL injuries at 0° of knee flexion. While the amount of gapping in extension was less than that seen at 20°, this observation does demonstrate that an isolated medial knee injury will produce medial compartment gapping in extension. In addition, we found that the amount of medial compartment gapping in extension was significantly more for a combined PCL and medial knee injury than for a combined ACL and medial knee injury. Thus, the amount of medial gapping detected on clinical examination with the knee in full extension (0° of flexion) should be correlated with increases in anterior or posterior translation on clinical examination or magnetic resonance imaging scans to assess for possible combined cruciate ligament injuries in addition to medial knee injuries.

For most medial knee injuries, it has been reported that the patterns of injury for the majority of patients are either torn off the femur (meniscofemoral-based) or tibia (meniscotibial-based) compared with a lower incidence of intrasubstance injuries.[45] It has also been reported that for isolated medial knee injuries, meniscofemoral-based tears have a higher rate of healing than meniscotibial-based tears.[3,27,42,49] Thus, we chose 2 different sectioning sequences to create both complete meniscofemoral- and meniscotibial-based tears to discern if there was a measurable difference in medial compartment gapping between these 2 injury conditions. Although we found a significant increase in gapping for the meniscofemoral-based lesions compared with the meniscotibial-based lesions, the difference in gapping between the 2 sectioning states was only between 0.7 to 1.7 mm, which we believe would not be a clinically important difference in medial compartment gapping between meniscofemoral-based and meniscotibial-based medial knee injuries based on valgus stress radiographs. Thus, for acute injuries, one must rely on the location of pain on the clinical examination or utilize magnetic resonance imaging scans to discern whether a medial knee injury is primarily torn off the femur or the tibia rather than being able to differentiate these injuries on valgus stress radiographs.

Under loading conditions similar to this study, previous studies examining valgus stress radiographs in normal knees have reported that the average physiological side-to-side variation for medial compartment opening is less than 2.0 mm at 20° of flexion.[21,22,39,44,50] These side-to-side variation studies are important because they set a baseline for the amount of medial compartment gapping that can be considered normal, and above which would define an injury. Thus, the results in this study demonstrate that the amount of medial compartment gapping at 20° of knee flexion created by either a proximal or distal sMCL tear was more than the previously reported normal side-to-side variability, which validates the use of valgus stress radiographs to objectively diagnose medial knee injury.

New techniques for anatomical surgical reconstruction of medial knee injuries have been proposed recently.[6,7,8] For that reason, it has become increasingly important to be able to quantify the extent to which both established and emerging medial knee reconstruction procedures have restored knee stability. We believe that valgus stress radiographs are a feasible and cost-effective objective measurement tool both for the clinician to document their patients' postoperative results and also to allow the results of future research to be more easily compared and understood. It is also important to fully understand the laxity and gapping associated with combined medial injuries because these injuries have been reported in some patients to have detrimental sequelae if left untreated, with continued instability, muscle weakness, posttraumatic arthritis, and significantly lower Lysholm scores in patients with multiple ligament knee injuries.[8,15,20,24,36,43,45] Therefore, valgus stress radiographs can provide a means to aid in diagnosing both acute and chronic combined medial knee injuries to minimize the occurrence of these potentially adverse outcomes.

One of the limitations of our study was that cyclic loading of the cadaveric knee specimens over time may have artificially increased the amount of medial knee opening by weakening the in vitro ligaments. A second limitation of this study was that while the use of 2 sectioning protocols attempted to replicate common patterns of injury, without performing all combinations of sectioning, medial compartment gapping could vary with injury combinations not performed in this study. In addition, our study was performed on older cadaveric specimens for which we could not apply higher loads because the cruciate ligaments consistently tore with application of higher test loads after all of the medial knee structures were sectioned. However, this observation would indicate that one must be careful in applying a large clinical valgus load to a knee with a severe medial knee structure injury because it could lead to further injury of an intact or partially torn cruciate ligament.[16]

In conclusion, we found that the amount of medial compartment gapping can be quantitated on valgus stress radiographs for medial knee injuries. Valgus stress radiographs can be a valuable adjunct to one's clinical examination to quantitate the amount of medial compartment gapping both after injury and after treatment for medial knee injuries. We found that medial compartment gapping does occur in extension for an isolated medial knee injury. In addition, we found no clinically important differences in medial gapping between either a meniscofemoral- or meniscotibial-based medial knee injury on valgus stress radiographs.

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