AJSM PreView, published on July 16, 2009 as doi:10.1177/0363546509333852

Winner of the Herodicus Award

Medial Knee Injury

Part 1, Static Function of the Individual Components of the Main Medial Knee Structures

Chad J. Griffith,* MD, Robert F. LaPrade,*† MD, PhD, Steinar Johansen,‡ MD, Bryan Armitage,* MSc, Coen Wijdicks,* MSc, and Lars Engebretsen,‡ MD, PhD
*From the *Division of Sports Medicine, Department of Orthopaedic Surgery, University of Minnesota, Minneapolis, Minnesota, and the ‡Orthopaedic Center, Ullevaal University Hospital, and Faculty of Medicine, University of Oslo, Oslo, Norway*

Background: There is a lack of knowledge on the primary and secondary static stabilizing functions of the posterior oblique ligament (POL), the proximal and distal divisions of the superficial medial collateral ligament (sMCL), and the meniscofemoral and meniscotibial portions of the deep medial collateral ligament (MCL).

Hypothesis: Identification of the primary and secondary stabilizing functions of the individual components of the main medial knee structures will provide increased knowledge of the medial knee ligamentous stability.

Study Design: Descriptive laboratory study.

Methods: Twenty-four cadaveric knees were equally divided into 3 groups with unique sequential sectioning sequences of the POL, sMCL (proximal and distal divisions), and deep MCL (meniscofemoral and meniscotibial portions). A 6 degree of freedom electromagnetic tracking system monitored motion after application of valgus loads (10 N·m) and internal and external rotation torques (5 N·m) at 0°, 20°, 30°, 60°, and 90° of knee flexion.

Results: The primary valgus stabilizer was the proximal division of the sMCL. The primary external rotation stabilizer was the distal division of the sMCL at 30° of knee flexion. The primary internal rotation stabilizers were the POL and the distal division of the sMCL at all tested knee flexion angles, the meniscofemoral portion of the deep MCL at 20°, 60°, and 90° of knee flexion, and the meniscotibial portion of the deep MCL at 0° and 30° of knee flexion.

Conclusion: An intricate relationship exists among the main medial knee structures and their individual components for static function to applied loads.

Clinical Significance: Interpretation of clinical knee motion testing following medial knee injuries will improve with the information in this study. Significant increases in external rotation at 30° of knee flexion were found with all medial knee structures sectioned, which indicates that a positive dial test may be found not only for posterolateral knee injuries but also for medial knee injuries.

Keywords: posterior oblique ligament; superficial medial collateral ligament; deep medial collateral ligament; sequential sectioning; dial test

The medial side of the knee is composed of 1 large ligament and a complex arrangement of joint capsular thickenings and tendinous attachments. Previous studies have demonstrated that the superficial medial collateral ligament (MCL), deep MCL, and posterior oblique ligament (POL) are the main static stabilizing structures of the medial knee.[1,3,7,11,12] Although the presence of the superficial MCL, the meniscofemoral and meniscotibial divisions of the deep MCL, and the POL are well documented in the literature, descriptions of the anatomy of these main medial knee structures has varied somewhat in previous qualitative studies.[1,7,12] One recent study quantitatively defined the courses and attachment sites of the main stabilizing structures of the medial knee.[9] This quantitative study described a proximal and distal division of the superficial MCL, with a femoral attachment, a proximal tibial attachment, and a more distal tibial attachment, similar to previous descriptions.[1,9] Finally, the quantitatively described anatomy of the POL reinforced and supplemented

†Address correspondence to Robert F. LaPrade, MD, PhD, Director, University of Minnesota Biomechanics Lab, Department of Orthopaedic Surgery, University of Minnesota, 2450 Riverside Avenue South, R200, Minneapolis, MN 55454 (e-mail: lapra001@umn.edu).

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. X, No. X
DOI: 10.1177/0363546509333852

its original description, which reported that the main component of the POL was the central arm, with attachments to the direct arm of the semimembranosus muscle, posteromedial capsule, and medial meniscus.[8,9]

Previous sequential sectioning studies have demonstrated that the medial knee structures have important primary and secondary roles in providing stability against abnormal valgus motion, external and internal rotation, and anterior and posterior translation in the knee.[2,10] However, none of these previous biomechanical studies have differentiated between the 2 conjoined but distinct divisions of the superficial MCL ligament and the deep MCL. As we move toward more anatomic reconstructions, it is important that we fully understand the differences between the individual components of these main medial knee stabilizing structures. Furthermore, many previous biomechanical studies have inferred the function of the medial knee structures based on the decreased force required to obtain the same motion as the intact knee.[13] Although this testing method can be useful and informative, it does not yield information regarding the amount of abnormal motion that would be seen in an injury state, which is important in the interpretation of preoperative and postoperative clinical examinations. A recent study conducted by our group, using the same specimens used in the present study, directly measured the tensile loads experienced by the main medial knee structures in the intact knee.[5] This study supplemented the understanding of medial knee biomechanics by quantitatively reporting on the distinct importance of the distal division of the superficial MCL in response to valgus moments and the previously underestimated function of the POL in resisting internal rotation torque near extension.

Our hypothesis was that the identification of the primary and secondary stabilizing functions of the individual components of the main medial knee structures would provide increased knowledge of the ligamentous stability of the medial knee, which had not been described well in the literature. The purpose of this study was to obtain a comprehensive description of the biomechanical sequelae resulting from injuries to the individual components of the medial knee structures. In the first part of this study, we examined the primary and secondary stabilizing functions of the POL, the proximal and distal divisions of the superficial MCL, and the meniscofemoral and meniscotibial components of the deep MCL to applied loads through a sequential sectioning biomechanical study. In the second part of this study, we investigated the redistribution of loads on the superficial MCL and POL after medial knee structure sectioning.

MATERIALS AND METHODS

Specimen Preparation

This study used 24 nonpaired fresh-frozen cadaveric knees with no evidence of prior injury or abnormality and with an average age of 69.5 years (range, 45-87). Approximately 5 cm of the ends of the proximal femur and the distal tibia/fibula were stripped of all soft tissues and severed 20 cm proximal to the knee joint and 12.5 cm distal to the knee joint, respectively. The proximal femur was then cemented in a mold using PMMA (polymethylmethacrylate). The tibial intramedullary canal was reamed with a 13-mm drill bit, and a threaded rod was inserted into the shaft of the tibia (parallel to the long axis of the tibia) and fixed with PMMA to prevent any rotation of the rod. A lock nut was secured to the end of the tibial rod for application of internal and external rotation torques.

The semitendinosus, gracilis, and sartorius muscles and tendons were detached, and deeper dissection isolated the proximal and distal divisions of the superficial MCL, the POL, and the meniscofemoral and meniscotibial divisions of the deep MCL. The specimen was mounted into a previously described customized aluminum apparatus that firmly secured the femur at a horizontal angle while allowing uninhibited movement of the tibia and fibula at fixable flexion angles.[5]

Measurements

Motion of the tibia relative to the static femur was quantified using the Polhemus Liberty system (Polhemus Inc, Colchester, Vermont). Two receivers were bicortically attached to the specimen using threaded Kirschner wires (K-wires) at the anterior midfemur and on the anterior tibial crest distal to the tibial tubercle. The positions of the most medial, lateral, anterior, and anteromedial landmarks on the articular cartilage margins of the tibial plateau were obtained with the Polhemus digitizing stylus to establish a 3-dimensional Cartesian coordinate system for the tibial receiver. Establishing this coordinate system allowed us to properly identify the tibiofemoral joint line as the fulcrum for valgus angulation, internal rotation, and external rotation. Furthermore, the neutral position within this coordinate system was established for each testing angle before any load application or sectioning of structures. Therefore, it was possible to measure all knee motion during the sequential sectioning sequences relative to the neutral positions of the intact knee. During load application, Motion Monitor software (Innovative Sports Training, Chicago, Illinois), integrated with the Polhemus system, detected positional changes of the tibia relative to the static femoral receiver, which allowed for characterization of the motion of the tibial coordinate system relative to the static femoral receiver.

External Force Application

Each knee was tested at 0°, 20°, 30°, 60°, and 90° of flexion. Three sequential sectioning sequences, with 8 knees in each sequence, were performed involving sectioning of the POL, 1 cm distal to its femoral attachment; the superficial MCL, at its femoral and distal tibial attachments; and the deep MCL, horizontally at the midsubstance of its meniscofemoral and meniscotibial divisions (Table 1). Even though we used the largest number of specimens for any medial knee biomechanics study, we were still limited in the number of sectioning sequences that could be performed. The chosen sectioning sequences were based on injury pattern knowledge from our 2 centers and on

TABLE 1
Sequential Sectioning Groups[a]

Group[b]	Cutting Sequence
1	Intact → POL → MF → MT → distal sMCL → proximal sMCL → sectioned
2	Intact → MF → MT → distal sMCL → proximal sMCL → POL → sectioned
3	Intact → distal sMCL → proximal sMCL → POL → MF → MT → sectioned

[a]Arrow indicates a cut. POL, posterior oblique ligament; MF, meniscofemoral attachment of deep medial collateral ligament; MT, meniscotibial attachment of deep medial collateral ligament; sMCL, superficial medial collateral ligament.

[b]Per group: n = 8.

sequences that sectioned 1 of the main structures and its components first and last, which provided the greatest opportunity to define the primary and secondary stabilizing functions of these structures. The same examiner applied all external loads of 10 N·m valgus and 5 N·m internal and external rotation torques at each flexion angle and for each cut state. A Model SM S-type Load Cell (Interface, Scottsdale, Arizona), with a manufacturer-reported nonrepeatability error of ±0.01%, was used to apply varus/valgus loads on the tibial rod 22.9 cm from the joint line. A Model TS12 Shaft Style Reaction Torque Transducer (Interface), with a manufacturer-reported nonrepeatability error of ±0.02%, was used to apply internal and external rotation torques. All load and flexion angle combinations were applied 3 times for each sequential sectioning state, with the results averaged.

Experiment Validation

To validate the experimental design, measurements were repeated on 8 consecutive specimens, and intraspecimen measurements were compared to demonstrate the reproducibility and consistency of the biomechanical testing apparatus, Polhemus measurements, ligament properties, and external load application, for a complete intact testing sequence of all applied loads at all tested knee flexion angles. To minimize recall bias, 30 minutes of elapsed time was allotted between each series of intact measurements during the validation process.

Posttesting Analysis

Raw data were collected by the Motion Monitor software and were processed to output all sensor positions and tracked landmarks on the tibial plateau, relative to the femur sensor, which provided a consistent reference coordinate system for measurements of displacement and angulation. The data set from each test was imported into Matlab R2006b analysis software (The MathWorks, Natick, Massachusetts) for processing. The positional data were compared with the positions at the beginning and end of each test. Angulation was measured by monitoring angular changes in the coordinate systems of the sensors attached to the tibia. After the displacements or angulations were determined for each of the 3 applied loads, the calculated values were averaged to produce a single output value for each test state.

Statistical Analysis

Two-way analysis of variance was performed to compare each ligament's angular displacement to valgus loads and internal and external rotation torques for each flexion angle between sectioned states. Tukey's honest significant difference test was used for post hoc comparisons to detect significant differences between pairs of the load responses considered in each analysis of variance. Paired *t* tests were used to determine changes between the intact and all cut states for each tested load at each tested flexion angle. A significant difference was determined to be present for $P < .05$.

RESULTS

Numerical data for each sectioning group of 8 knees are reported in Appendices 1, 2, and 3 (available in the online version of this article at http://ajs.sagepub.com/supplemental/). For all comparisons, significant differences were determined between either a cut state and the intact state or between a cut state and the previous cut state. Significant differences with the intact state were mentioned for only the earliest cut state in the sequential sectioning order.

Validation Analysis

Intraspecimen comparison of repeated measurements was performed at each flexion angle for each loading condition in the intact state for 8 knees. The testing found the following average angulation differences between the 2 trials: for valgus loads, 0.56° ± 0.74°; for external rotation torques, 0.92° ± 1.19°; and for internal rotation torques, 0.85° ± 0.94°.

Valgus Rotation

Group 1. Initial sectioning of the POL did not produce a significant increase in valgus angulation, compared with the intact state, at any flexion angle (Figure 1A). Sectioning of both divisions of the deep MCL produced a significant increase in only valgus angulation, compared with the intact state, after sectioning of the meniscotibial portion of the deep MCL at 60° of knee flexion ($P < .05$). Further sectioning of the distal division of the superficial MCL yielded a significant increase in valgus angulation, compared with the intact state, at 0°, 20°, and 30° of knee flexion (all $P < .001$). The increase in valgus angulation after sectioning of the distal superficial MCL was significantly greater than the previous meniscotibial cut state at 0° of knee flexion ($P < .005$), 20° ($P < .01$), and 30° ($P < .01$). Further sequential sectioning of the proximal superficial MCL division produced a significant increase in valgus

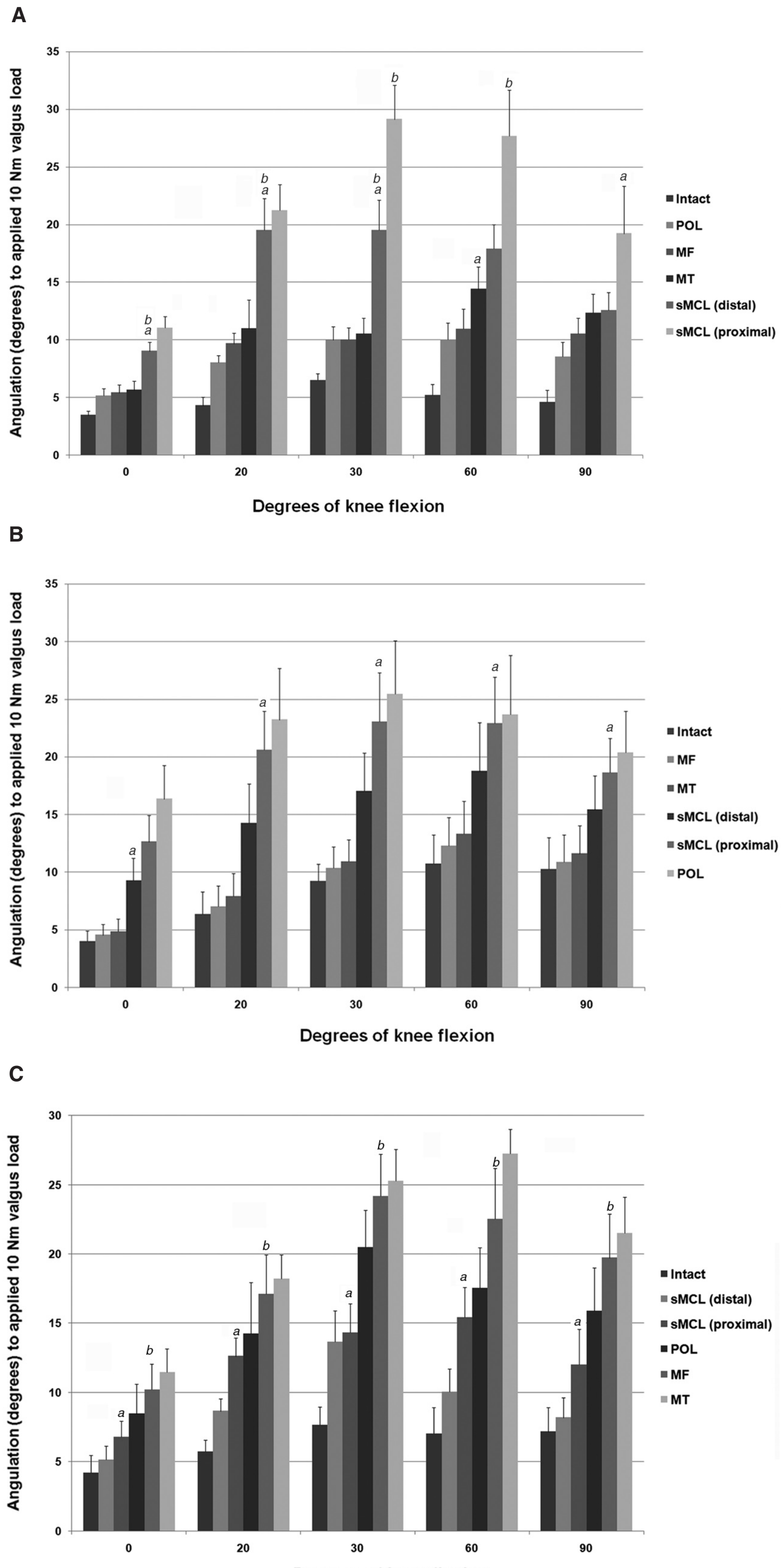

Figure 1. Knee angulation changes resulting from an applied valgus force (10 N·m) for each group of 8 sectioned knees. Testing conditions: A, group 1; B, group 2; C, group 3. [a]Significant difference compared with the intact knee (note that all subsequent sequential sectioning states are significantly different compared with the intact knee). [b]Significant difference compared with the previous sectioning state. Error bars indicate the standard error of the mean.

angulation, compared with the previous cut state, at 30° of flexion ($P < .005$) and 60° ($P < .05$); it also significantly increased at 90° of flexion ($P < .001$).

Group 2. Sectioning of both divisions of the deep MCL did not produce a significant increase in valgus angulation, compared with the intact state, at any knee flexion angle (Figure 1B). At 0° of knee flexion, sectioning of the distal superficial MCL division resulted in significantly increased valgus angulation, compared with the intact state ($P < .05$). Further sequential sectioning of the proximal division of the superficial MCL significantly increased valgus angulation, compared with the intact state, at 20° of knee flexion ($P < .005$), 30° ($P < .005$), 60° ($P < .01$), and 90° ($P < .01$). However, valgus angulation after sectioning of the proximal superficial MCL division was not significantly greater at any knee flexion angle, as compared with the previous cut state in which the distal superficial MCL division was sectioned. Additional sectioning of the POL did not produce any further significant increases in valgus angulation, compared with the previous cut state.

Group 3. Sectioning of the distal division of the superficial MCL did not produce a significant increase in valgus angulation, compared with the intact state at any knee flexion angle (Figure 1C). Further additional sectioning of the proximal division of the superficial MCL produced a significant increase in valgus angulation, compared with the intact state, at 0° of knee flexion ($P < .0001$), 20° ($P < .005$), 30° ($P < .005$), 60° ($P < .01$), and 90° ($P < .005$), but it did not cause a significant increase in valgus angulation, compared with the distal superficial MCL cut state at any knee flexion angle. Sectioning of the POL did not produce any significant increases in valgus angulation, compared with the previous cut state. Further sectioning of the meniscofemoral portion of the deep MCL significantly increased valgus angulation, compared with the previous sectioned POL cut state, at 0° of knee flexion ($P < .0001$), 20° ($P < .0001$), 30° ($P < .005$), 60° ($P < .005$), and 90° ($P < .0005$).

External Rotation

Group 1. Initial sectioning of the POL did not significantly increase external rotation, compared with the intact state at any flexion angle (Figure 2A). Further sequential sectioning of the meniscofemoral deep MCL significantly increased external rotation, compared with the intact state, at 30° and 90° of flexion (both $P < .05$), but it was not significantly increased over the previous cut state at any flexion angle. Further sectioning of the distal superficial MCL division yielded a significant increase in external rotation, compared with the intact state, at 0° of knee flexion ($P < .05$), 20° ($P < .005$), and 60° ($P < .005$). No cut states significantly increased external rotation, compared with the previous cut state, at any knee flexion angle.

Group 2. Sectioning of the meniscofemoral and meniscotibial divisions of the deep MCL did not significantly increase external rotation, compared with the intact state, at any knee flexion angle (Figure 2B). External rotation was significantly increased, compared with the intact state, at 30° of knee flexion after sectioning of the distal superficial MCL division ($P < .01$). With all structures sectioned, external rotation was significantly increased, compared with the intact state, only at 60° of knee flexion ($P < .005$). No tested cut states significantly increased external rotation, compared with the previous cut state, at any knee flexion angle.

Group 3. External rotation was significantly increased, compared with the intact state, after sectioning of the distal division of the superficial MCL ligament at 30° of knee flexion ($P < .005$) (Figure 2C). External rotation was not significantly increased at any knee flexion angle after sectioning of the proximal superficial MCL. Sectioning of the meniscofemoral deep MCL created a significant increase in external rotation, compared with the previous cut state, at 30° of knee flexion ($P < .05$). With all structures sectioned, external rotation was not significantly increased, compared with the intact state, at 0°, 20°, 60°, and 90° of knee flexion.

Internal Rotation

Group 1. Initial sectioning of the POL significantly increased internal rotation at 0° of knee flexion ($P < .005$), 20° ($P < .05$), 30° ($P < .05$), 60° ($P < .0001$), and 90° ($P < .05$), compared with the intact state (Figure 3A). Further sectioning of the meniscofemoral portion of the deep MCL significantly increased internal rotation, compared with the POL cut state, at 90° of knee flexion ($P < .05$). Sectioning of the meniscotibial portion of the deep MCL did not create further significant increases in internal rotation at any flexion angle, compared with the previous cut state, with a sectioned meniscofemoral portion of the deep MCL. Sectioning of the distal division of the superficial MCL created a significant increase in internal rotation, compared with the previous cut state, at 0° of knee flexion ($P < .05$). Further sectioning of the proximal division of the superficial MCL significantly increased internal rotation at 0° of knee flexion, compared with the previous cut state, in which the distal division of the superficial MCL had been sectioned ($P < .01$).

Group 2. Initial sectioning of the meniscofemoral portion of the deep MCL significantly increased internal rotation, compared with the intact state, at 20° of flexion ($P < .0005$), 60° ($P < .0001$), and 90° ($P < .001$) (Figure 3B). Further sequential sectioning of the meniscotibial division of the deep MCL resulted in significantly increased internal rotation, compared with the intact state, at 0° of knee flexion ($P < .05$) and 30° ($P < .0001$), and it significantly increased internal rotation, compared with the previous cut state, at 30° ($P < .05$) and 90° ($P < .05$). There was a significant increase in internal rotation, compared with the previous cut state, after sectioning of the proximal superficial MCL and POL at 30° of flexion ($P < .05$) and 90° ($P < .05$), respectively. There were no other significant increases in internal rotation after sectioning of the POL.

Group 3. Initial sectioning of the distal superficial MCL division significantly increased internal rotation, compared with the intact state, at all flexion angles: 0° ($P < .005$), 20° ($P < .0001$), 30° ($P < .0001$), 60° ($P < .0001$),

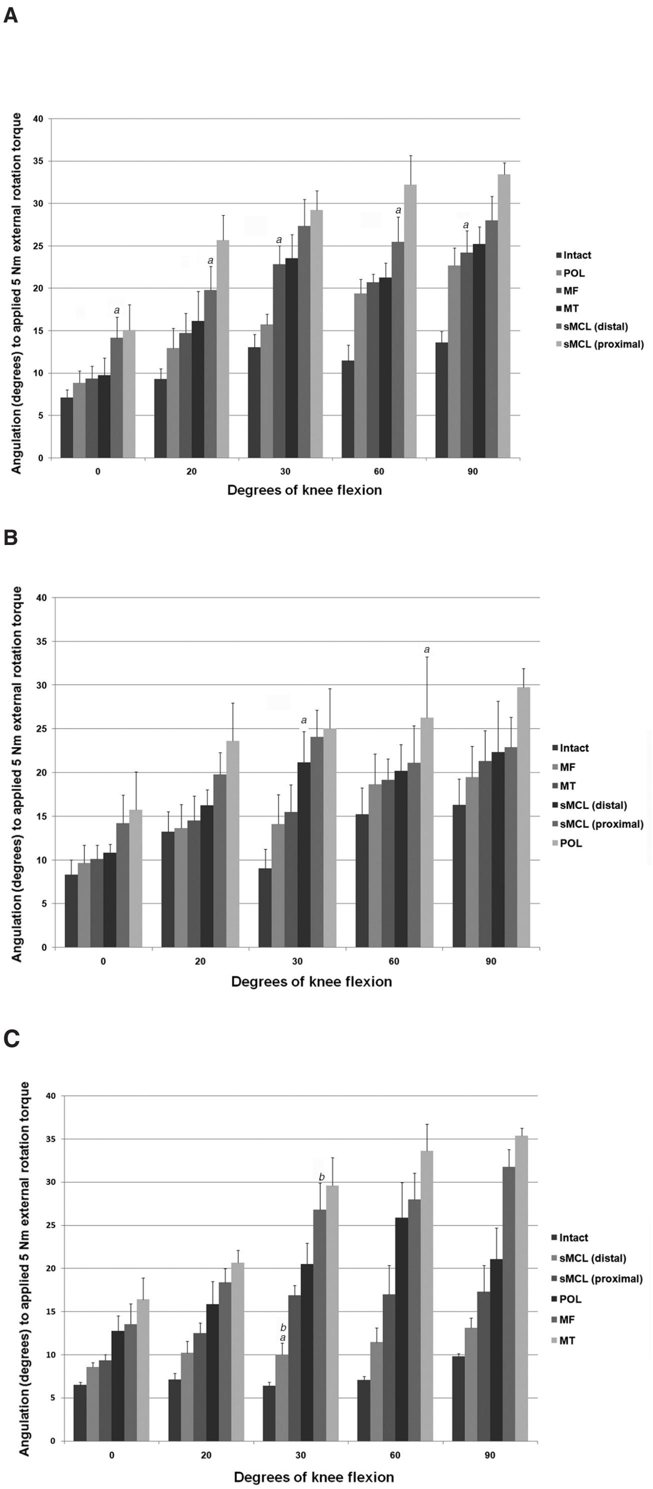

Figure 2. Knee angulation changes resulting from an applied external rotation torque (5 N·m) for each group of 8 sectioned knees. Testing conditions: A, group 1; B, group 2; C, group 3. [a]Significant difference compared with the intact knee (note that all subsequent sequential sectioning states are also significantly different compared with the intact knee). [b]Significant difference compared with the previous sectioning state. Error bars indicate the standard error of the mean.

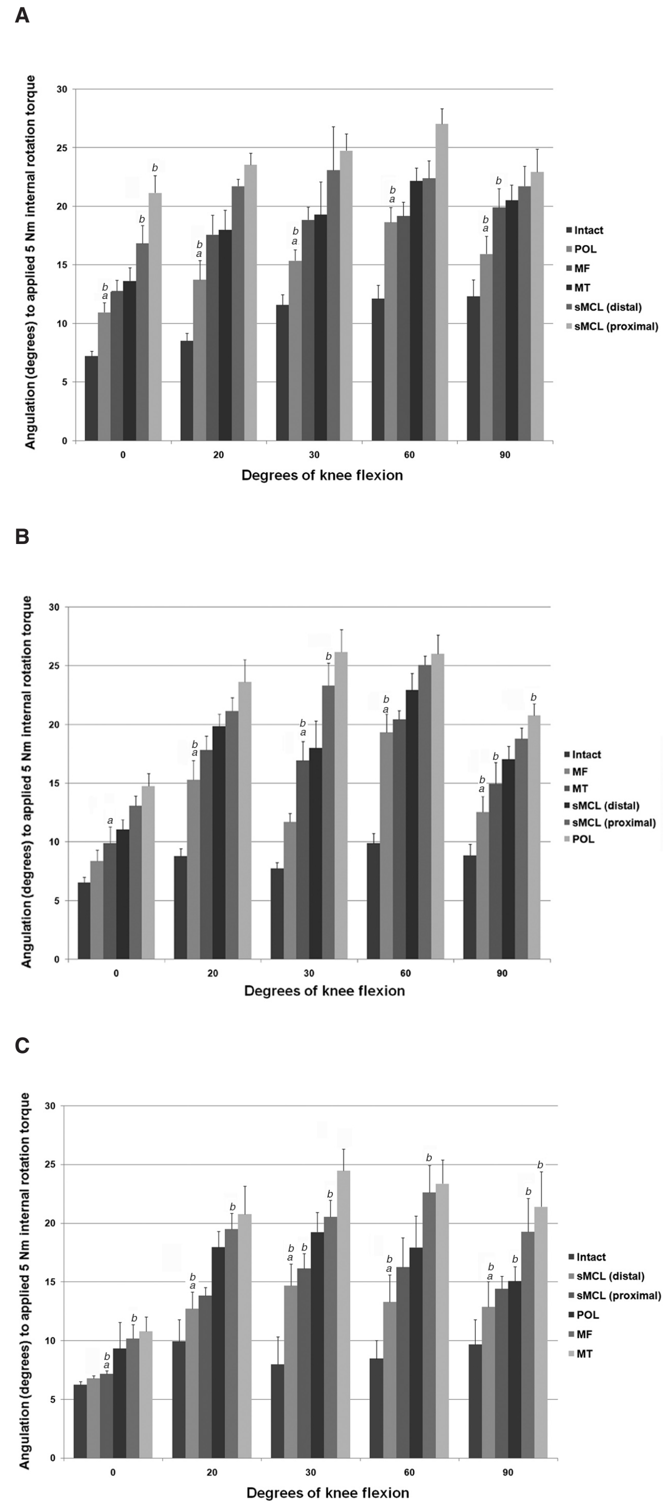

Figure 3. Knee angulation changes resulting from an applied internal rotation torque (5 N·m) for each group of 8 sectioned knees. Testing conditions: A, group 1; B, group 2; C, group 3. [a]Significant difference compared with the intact knee (note that all subsequent sequential sectioning states are also significantly different compared with the intact knee). [b]Significant difference compared with the previous sectioning state. Error bars indicate the standard error of the mean.

TABLE 2
Increases in Motion Limits Relative to the Intact Knee: Angulation per Applied Moment[a] (mean ± standard error of the mean)

	Degrees of Flexion				
Angulation	0°	20°	30°	60°	90°
Valgus	9.4 ± 1.5	16.2 ± 2.0	19.2 ± 2.1	18.1 ± 2.3	12.8 ± 2.0
External rotation	8.3 ± 2.0	14.3 ± 1.7	18.9 ± 2.2	20.9 ± 2.5	21.2 ± 1.1
Internal rotation	10.6 ± 1.5	13.8 ± 0.9	15.3 ± 0.9	15.6 ± 1.1	11.4 ± 1.2

[a]Increases occurred with sectioning of the superficial medial collateral ligament, deep medial collateral ligament, and posterior oblique ligament.

and 90° ($P < .0001$) (Figure 3C). There was a significant increase in internal rotation, compared with the previous cut state, after sectioning of the proximal division of the superficial MCL and POL at 30° of flexion ($P < .05$) and 90° ($P < .05$), respectively. Further sequential sectioning of the meniscofemoral division of the deep MCL produced a significant increase in internal rotation, compared with the previous cut state, at all flexion angles: 0° ($P < .0005$), 20° ($P < .0001$), 30° ($P < .0001$), 60° ($P < .001$), 90° ($P < .0001$). Sequentially sectioning the meniscotibial division of the deep MCL significantly increased internal rotation, compared with the previous cut state, at 30° of knee flexion ($P < .05$) and 90° ($P < .0001$).

All Groups Combined (All Tested Medial Structures Sectioned). With the measurements for all 24 knees combined, sectioning of the medial ligaments resulted in a significant increase in valgus angulation, compared with the intact state, by 9.4°, 16.2°, 19.2°, 18.1°, and 12.8° at 0°, 20°, 30°, 60°, and 90° of knee flexion, respectively ($P < .001$ for all states) (Table 2). External rotation significantly increased by 8.3°, 14.3°, 18.9°, 20.9°, and 21.2° for 0°, 20°, 30°, 60°, and 90°, respectively ($P < .001$ for all states). Internal rotation also significantly increased by 10.6°, 13.8°, 15.3°, 15.6°, and 11.4° for 0°, 20°, 30°, 60°, and 90°, compared with the intact state, respectively ($P < .001$ for all states).

DISCUSSION

Little new data have been published on injuries to the medial side of the knee. Overall, the biomechanical function of the individual structures of the medial knee has been relatively neglected in recent years. In addition, there has been no consensus on the primary and secondary roles of individual components of the main medial knee structures to providing knee stability. Therefore, it is difficult to determine, on clinical examination alone, which structures may be injured and which may need to be reconstructed in patients with abnormal knee laxity.

Our quantitative data support our hypothesis that the individual components and overall structures of the 3 main medial knee static stabilizers have important primary and secondary stabilization roles in valgus, external rotation, and internal rotation for the medial knee. We were able to identify the main individual structures and their individual components that were responsible for increased joint motion in the face of medial knee injuries. We found that there is a hierarchy of structures that restrain abnormal knee motion in the presence of a medial knee injury. Knowledge of which components and individual structures are the primary and secondary stabilizers should increase the effectiveness of a clinical examination in diagnosing medial knee injuries.

The multiple sectioning sequences in this study permitted further definition of the primary and secondary stabilization roles of the main individual structures and their components. In this study, we found that the proximal division of the superficial MCL was the primary static stabilizer to valgus motion at all tested flexion angles, whereas the secondary valgus stabilizers were the meniscofemoral portion of the deep MCL at all tested flexion angles and the meniscotibial portion of the deep MCL at 60° of knee flexion. For external rotation, the primary stabilizer was the distal division of the superficial MCL at 30°. The secondary external rotation stabilizers were the distal division of the superficial MCL at 0°, 20°, and 60° of flexion; the proximal division of the superficial MCL at 90° of flexion; the meniscofemoral portion of the deep MCL at 30° and 90° of flexion; and the POL at 30° of flexion. The primary stabilizers for internal rotation were the POL at all tested flexion angles; the meniscofemoral portion of the deep MCL at 20°, 60°, and 90° of flexion; and the distal division of the superficial MCL at all tested knee flexion angles. The secondary internal rotation stabilizers were the proximal division of the superficial MCL at 0°, 30°, and 90° of flexion; the meniscofemoral portion of the deep MCL at 0° and 30° of flexion; and the meniscotibial portion of the deep MCL at 0°, 30°, and 90° of flexion.

Most of the previous literature describes the proximal and distal divisions of the superficial MCL as 1 functional unit. We can appreciate this description based on our observations: Whereas the proximal tibial attachment has a distinct adherence, this attachment was not as stout as the femoral or distal tibial attachments, because it attached primarily to soft tissues over the anterior arm of the semimembranosus muscle and not directly to bone.[9] When viewed as 1 functional unit, the static functions of the superficial MCL were primary valgus and internal rotation stabilization at all tested knee flexion angles, providing primary external rotation stabilization at 30° of knee flexion as well. In contrast, individual sectioning of the distal division did not significantly increase valgus motion, whereas individual sectioning of the proximal division resulted in a significant increase in valgus motion. This observation makes intuitive sense given that the distal division does not cross the joint line. Although the distal division does not function as a primary valgus stabilizer, we found that it does have an important primary role to providing external and internal rotational stability. We theorize that this function results because some of its fibers span the entire course of the superficial MCL ligament and injuries to the distal division disrupt these fibers, which results in rotational instability.

We recently reported differences in valgus load responses between the 2 superficial MCL divisions and in fact demonstrated a greater load response from the distal division, compared with the proximal division, at 60° of knee flexion.[5] To fully understand the biomechanics of the superficial MCL, it is important to properly interpret the implications of tensile force and motion information. The distal division has a tensile load response to valgus forces that is likely due to the more medial superficial MCL fibers that bypass the proximal tibial attachment.[5] Thus, injury to the distal division may predispose the proximal division to valgus injury because of the functional loss of the fibers that bypass the proximal tibial attachment. In this manner, the distal division has an indirect role in preventing abnormal valgus motion. This knowledge of the biomechanics of the superficial MCL emphasizes the necessity of surgically repairing or reconstructing both divisions of the superficial MCL to reproduce the primary valgus and rotatory stabilizing functions of the superficial MCL.

Compared with the number of studies on the function of the superficial MCL, there are fewer studies that report on the isolated function of the deep MCL. One study noted that it was not thought to be important in providing stability to the knee; as such, it was not cut in the study.[7] The previous sequential sectioning studies that evaluated the function of the deep MCL described it as a secondary restraint to valgus loads.[10] The deep MCL was also reported to provide restraint against external rotation torque in knees flexed greater than 30°.[10] Our study differs from the study by Robinson et al[10] in that we found significant increases in internal rotation with sectioning of the deep MCL, whereas they reported no significant increase for internal rotation at any flexion angle.

The POL has been reported to provide stability against valgus, internal rotation, and external rotation torques.[7,10] Studies have reported a minimal increase in valgus rotation with POL sectioning,[7,10] whereas our study found no significant role of the POL in resisting valgus rotation. For external rotation, Haimes et al[7] found minimal increases in external rotation for isolated sectioning of the POL, whereas Robinson et al[10] found increased external rotation at 30°. Haimes et al reported increases in external rotation near extension similar to those of our study for isolated sectioning of the POL, whereas Robinson et al found increases in internal rotation that were comparable to those of our study; however, our study found increases in external rotation at higher knee flexion angles.[7,10] In addition, our study demonstrated a significant primary stabilization role of the POL to internal rotation at all tested flexion angles.

Although grade 3 medial knee injuries can result in significant valgus instability, the amount of increased external rotation with these injuries is not always recognized. One of the important clinical implications of the findings of this significant increase in external rotation for grade 3 medial knee injuries is in the interpretation of the dial test at 30° and 90° of knee flexion.[4,6] Although a positive dial test has been commonly believed to be pathognomonic for a posterolateral knee injury,[4,6] we found that there was a significant increase in external rotation at 30° and 90° with all structures sectioned in this study. It can sometimes be difficult to distinguish between posterolateral and posteromedial injuries on physical examination, especially in larger patients or in patients with multiple knee ligament injuries, for whom it can be difficult to determine the neutral point of the knee. As Haimes et al[7] have noted, experienced clinicians may incorrectly assume that increased external rotation is due to a posterolateral knee injury when it is actually due to a medial knee injury. Therefore, if one suspects either an isolated medial injury or a posterolateral knee injury, one way to differentiate between them on clinical examination would be to assess whether there is an increase or decrease in external rotation for the dial test when the knee is flexed from 30° to 90°. If there is a decrease in external rotation as one flexes the knee to 90°, then it is more likely to be a posterolateral knee injury.[4,6] However, if there is no apparent decrease in external rotation, then it is more likely to be an isolated medial-side knee injury. In addition, if the dial test is performed in the prone position, the examiner would be blinded to whether the tibial rotation is occurring from an anteromedial versus posterolateral position. Therefore, if one suspects an isolated medial or posterolateral knee injury and has difficulty clinically determining the location of the joint line gapping and external rotation, a careful interpretation of the location of the tibial rotation, as well as the differences in the amount of external rotation between 30° and 90° while performing the dial test, would help to elucidate the probable injury location.

One limitation of this study was that it was a cadaveric sectioning study in an older group of knees. Because we did not test the overall strength of structures, we believe that the use of older specimens did not influence the results of the motion changes seen with individual sectioning of structures. In addition, we did not randomize the cutting order for the 2 divisions of the superficial MCL or the meniscofemoral and meniscotibial portions of the deep MCL. Therefore, some primary and secondary stabilization roles for the proximal division of the superficial MCL or the meniscotibial portion of the deep MCL may not have been discovered with our testing sequences.

In conclusion, we found that the individual components of the medial knee structures do have significant primary and secondary roles to valgus translation and external and internal rotation stabilization of the medial knee. In addition, we further identified that the 2 divisions of the superficial MCL have a complementary function, with the proximal division having a primary valgus stabilization role and with the distal division having a more important stabilization role in preventing external and internal rotation. Knowledge of the static function of the main medial knee structures will assist in the interpretation of clinical knee motion testing and so provide guidance to improved diagnosis of medial knee injuries. Finally, increases in external rotation at 30° and 90° of knee flexion indicate that a positive dial test may result from either posterolateral or medial knee injuries.

ACKNOWLEDGMENT

This research study was supported by a grant from the Research Council of Norway (Grant No. 175047/D15) and Health East, Norway (Grant No. 10703604). The authors wish to acknowledge the assistance of Adam Sunderland, MS, Sean Pietrini, BS, and Connor Ziegler, BS, in the preparation and testing portions of this article, as well as the Anatomy Bequest Program of the University of Minnesota.

REFERENCES

1. Brantigan OC, Voshell AF. The tibial collateral ligament: its function, its bursae, and its relation to the medial meniscus. *J Bone Joint Surg.* 1943;25:121-131.
2. Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee: a biomechanical study. *J Bone Joint Surg Am.* 1980;62:259-270.
3. Fischer RA, Arms SW, Johnson RJ, Pope MH. The functional relationship of the posterior oblique ligament to the medial collateral ligament of the human knee. *Am J Sports Med.* 1985;13:390-397.
4. Gollehon DL, Torzilli PA, Warren RF. The role of the posterolateral and cruciate ligaments in the stability of the human knee: a biomechanical study. *J Bone Joint Surg Am.* 1987;69:233-242.
5. Griffith CJ, Wijdicks CA, LaPrade RF, Armitage BM, Johansen S, Engebretsen L. Force measurements on the posterior oblique ligament and superficial medial collateral ligament proximal and distal divisions to applied loads. *Am J Sports Med.* 2009;37:140-148.
6. Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee: effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am.* 1988;70:88-97.
7. Haimes JL, Wroble RR, Grood ES, Noyes FR. Role of the medial structures in the intact and anterior cruciate ligament-deficient knee: limits of motion in the human knee. *Am J Sports Med.* 1994;22:402-409.
8. Hughston JC, Eilers A. The role of the posterior oblique ligament in repairs of acute medial (collateral) ligament tears of the knee. *J Bone Joint Surg Am.* 1973;55:923-940.
9. LaPrade RF, Engebretsen AH, Ly TV, Johansen S, Wentorf FA, Engebretsen L. The anatomy of the medial part of the knee. *J Bone Joint Surg Am.* 2007;89:2000-2010.
10. 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.
11. Robinson JR, Sanchez-Ballester J, Bull AM, Thomas RW, Amis AA. The posteromedial corner revisited: an anatomical description of the passive restraining structures of the medial aspect of the human knee. *J Bone Joint Surg Br.* 2004;86:674-681.
12. Warren LF, Marshall JL. The supporting structures and layers on the medial side of the knee: an anatomical analysis. *J Bone Joint Surg Am.* 1979;61:56-62.
13. Woo SL, Debski RE, Withrow JD, Janaushek MA. Biomechanics of knee ligaments. *Am J Sports Med.* 1999;27:533-543.