Tibiofemoral Contact Mechanics After Serial Medial Meniscectomies in the Human Cadaveric Knee

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Background: There is no consensus regarding the extent of meniscectomy leading to deleterious effects on tibiofemoral contact mechanics.

Hypothesis: The meniscus aids in optimizing tibiofemoral contact mechanics, increasing contact area, and decreasing contact stress.

Study Design: Controlled laboratory study.

Methods: Twelve fresh-frozen human cadaveric knees each underwent 15 separate testing conditions—5 serial 20-mm posterior medial meniscectomy conditions (intact, 50% radial width, 75% radial width, segmental, and total meniscectomy) at 3 flexion angles (0°, 30°, and 60°)—under an 1800-N axial load. Tekscan sensors were used to measure total force and medial force, contact area, mean contact stress, and peak contact stress.

Results: All posterior medial meniscectomy conditions resulted in significantly decreased contact areas and increased mean and peak contact stresses compared with the intact state ($P < .05$). The changes in contact mechanics after segmental and total posterior medial meniscectomies were not statistically different ($P > .05$). Incremental changes in contact area and mean contact stress increased as more peripheral portions of the medial meniscus were removed, whereas peak contact stresses exhibited similar incremental changes throughout all meniscectomy conditions.

Conclusions: The meniscus is a crucial load-bearing structure, optimizing contact area and minimizing contact stress. Loss of hoop tension (ie, segmental meniscectomy) is equivalent to total meniscectomy in load-bearing terms. The peripheral portion of the medial meniscus provides a greater contribution to increasing contact areas and decreasing mean contact stresses than does the central portion, whereas peak contact stresses increase proportionally to the amount of meniscus removed.

Clinical Relevance: Because the degree of meniscectomy leading to clinically significant outcomes is unknown, a prudent strategy is to preserve the greatest amount of meniscus possible.

Keywords: knee biomechanics; tibiofemoral contact mechanics; contact area; contact stress; medial meniscus; meniscectomy; Tekscan

In 1897, Bland-Sutton described the meniscus as "the functionless remnants of intra-articular leg muscles."[10(p168)] Fifty-one years later, Fairbank[17] first noted on radiographs the increased incidence of degenerative changes in the knee occurring after total meniscectomy and proposed the role of the menisci in load transmission across the knee. Subsequently, numerous studies have reported the long-term effects of total[#] and partial meniscectomy.[11,14,18,23,24,39,47,50] Techniques including arthrography,[32,37] load-deflection studies,[34,35,41,51] intra-articular casting,[55,56] photoelastic studies,[46]

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direct intra-articular measurements,[2,12,54] and most recently the use of pressure-sensitive film[7,8,20,25] have been employed to elucidate the biomechanical effects of meniscectomy on the knee. The majority of this work has compared the intact knee with that after total meniscectomy. Two studies[7,25] have evaluated the effects of partial medial meniscectomy, but conclusions are limited secondary to small sample sizes. Currently, there is no consensus regarding at which point a partial meniscectomy leads to deleterious effects in the ipsilateral compartment. Thus, repairs of meniscal tears extending even into the white-white zone have been advocated to preserve the greatest amount of meniscus possible.[49]

During the past decade, the importance of the meniscus in maintaining the integrity of the tibiofemoral joint has been emphasized to a heightened level because of emerging alternatives for meniscal substitution or replacement. Restoration of the meniscus in a manner that duplicates native healthy meniscal function has the potential not only of resolving pain but also to restore the protective function the native meniscus is known to have for the articular cartilage surface. In this study, we chose to evaluate the biomechanical effects of serial meniscectomies in the posterior segment of the medial meniscus for 2 reasons. First, the majority of meniscal injuries occur in the medial compartment.[23,42,48] Second, the posterior portion of the medial meniscus carries a greater proportion of the load compared with the anterior segment.[2,51,55] The purpose of this study was to evaluate the changes in tibiofemoral contact areas and stresses after defined serial meniscectomies of the posterior segment of the medial meniscus.

MATERIALS AND METHODS

Specimen Preparation and Testing

Twelve fresh-frozen human cadaveric knees were obtained from 5 men and 7 women with an average age of 53 years (range, 38-61 years). Before dissection, each knee was visually inspected through a peripatellar arthrotomy to confirm that the menisci were intact and the joint surfaces were free from arthritic changes. Skin, subcutaneous fat, muscle, and patella were removed, leaving all but the anterior portion of the joint capsule intact. The cruciate and collateral ligaments were not disturbed. The femur and the tibia and fibula were then transected approximately 15 cm above and below the joint line, respectively. The tibia and fibula were cemented in a 3.5 × 4-inch (D × H) polyvinyl chloride (PVC) pipe with polymethyl methacrylate (PMMA), carefully orienting the tibial plateau parallel to the testing surface to minimize preferential overloading of either compartment of the knee. Two parallel tunnels were drilled into the femur medial to lateral, with care taken to avoid the origins of the collateral and cruciate ligaments. The distal femoral tunnel was oriented parallel to the tibial plateau and served as a pivot point, while the proximal tunnel allowed for selection of varying knee flexion angles. An osteotomy of the medial femoral condyle was then performed using a technique similar to the one devised by Martens et al[38] to facilitate repeated access to the medial hemijoint (Figure 1). These authors demonstrated that their osteotomy of the medial

Figure 1. Knee specimen with an osteotomy of the medial femoral condyle and 2 parallel femoral tunnels. Anterior bird's-eye view (A), medial bird's-eye view (B), and medial head-on view (C).

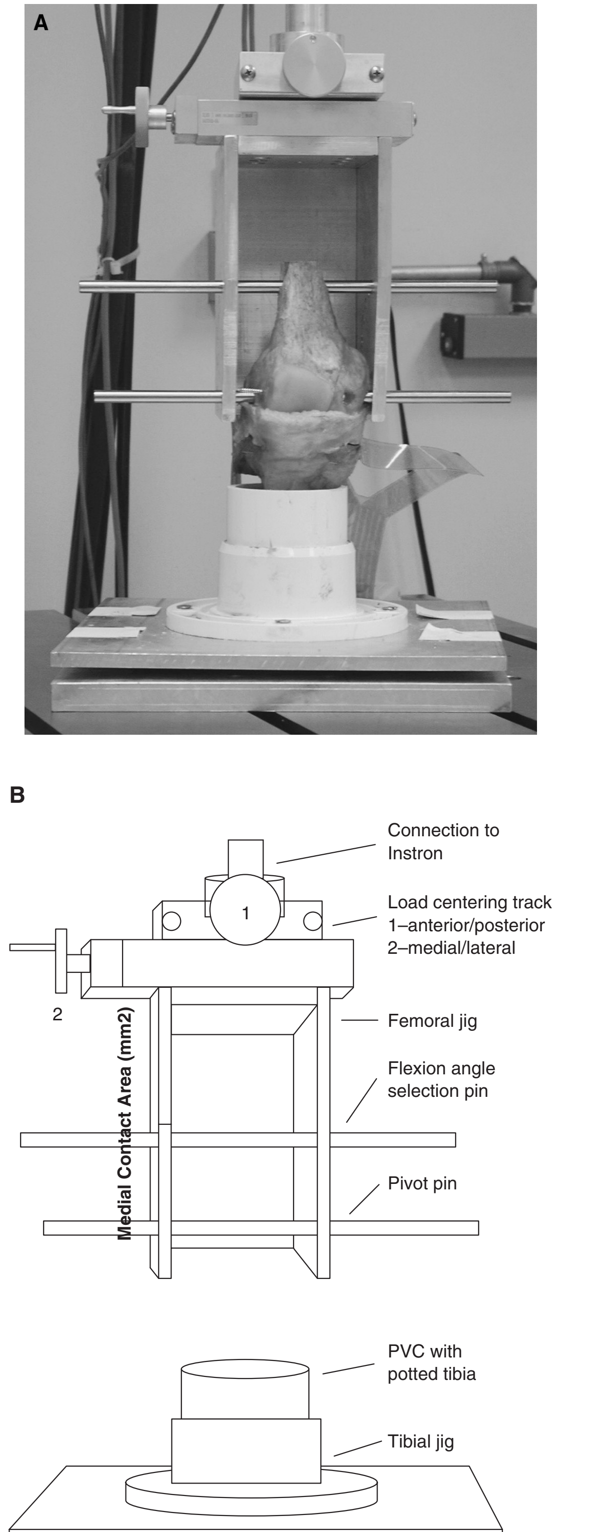

Figure 2. Knee specimen setup at 0° of flexion. Actual setup with K-Scan 4000 sensor exiting posteriorly (A); schematic of setup (B). Load centering is adjusted through the knobs labeled 1 (anterior/posterior) and 2 (medial/lateral). The space between the tibial jig and base plate consists of a ball-bearing surface to allow freedom of translational and rotational motions. PVC, polyvinyl chloride pipe.

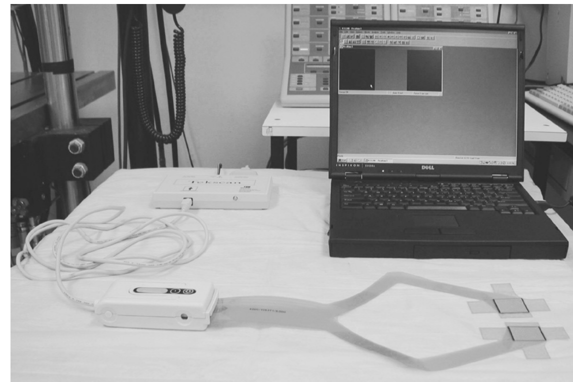

Figure 3. K-Scan 4000 system: IBM-compatible personal computer laptop, electronic pressure transducer, and a data acquisition box connecting the two. The horseshoe-shaped K-Scan 4000 sensor is composed of two 28 × 33-mm (924 mm^2) sensor pads, each with 2288 sensels (sensing elements).

femoral condyle did not significantly alter tibiofemoral contact mechanics compared with the intact knee. Our own pilot study confirmed this observation.

The femur was placed in the femoral jig at 0° of flexion. The tibia and fibula potted in PVC were inserted into the tibial jig and placed on a linear motion X-Y table that allowed for freedom of translational and rotational motions to minimize any abnormal stresses experienced as the result of shear forces (Figure 2). This setup resulted in 4 degrees of freedom, with flexion angle and varus/valgus moment being constrained. Instantaneous intra-articular contact area and stress measurements were obtained using the K-Scan 4000 system (Tekscan Inc, South Boston, Mass), consisting of a plastic laminated, thin-film (0.1 mm) electronic pressure transducer, hardware and software for an IBM-compatible personal computer, and a coupler connecting the two (Figure 3). The sensor was carefully placed below the menisci by creating small anterior and posterior horizontal capsulotomies in the medial and lateral compartments. The specimen was then mounted in an Instron 1321 materials testing device (Instron, Canton, Mass), with the joint initially unloaded and anatomically positioned to allow joint compression to be applied centrally to both condyles. Immediately before the testing of each specimen, a new sensor was carefully conditioned and calibrated according to the manufacturer's guidelines to minimize the effects of drift (change in sensor output when a constant force is applied over time), hysteresis (difference in sensor output response during loading and unloading at the same applied force), and sensitivity to temperature changes. The sensor was conditioned by subjecting it to 3 cycles of axial loading from 0 to 2800 N. It was then calibrated at 700 and 2100 N, generating a 2-point calibration curve specific for each knee and sensor combination. The K-Scan sensors in our study had an effective stress range from 0.5 to 30 MPa.

All specimens underwent 5 posterior medial meniscectomy conditions: (1) intact medial meniscus, (2) 50% radial width medial meniscectomy simulating a meniscectomy extending into the red-white zone, (3) 75% radial width

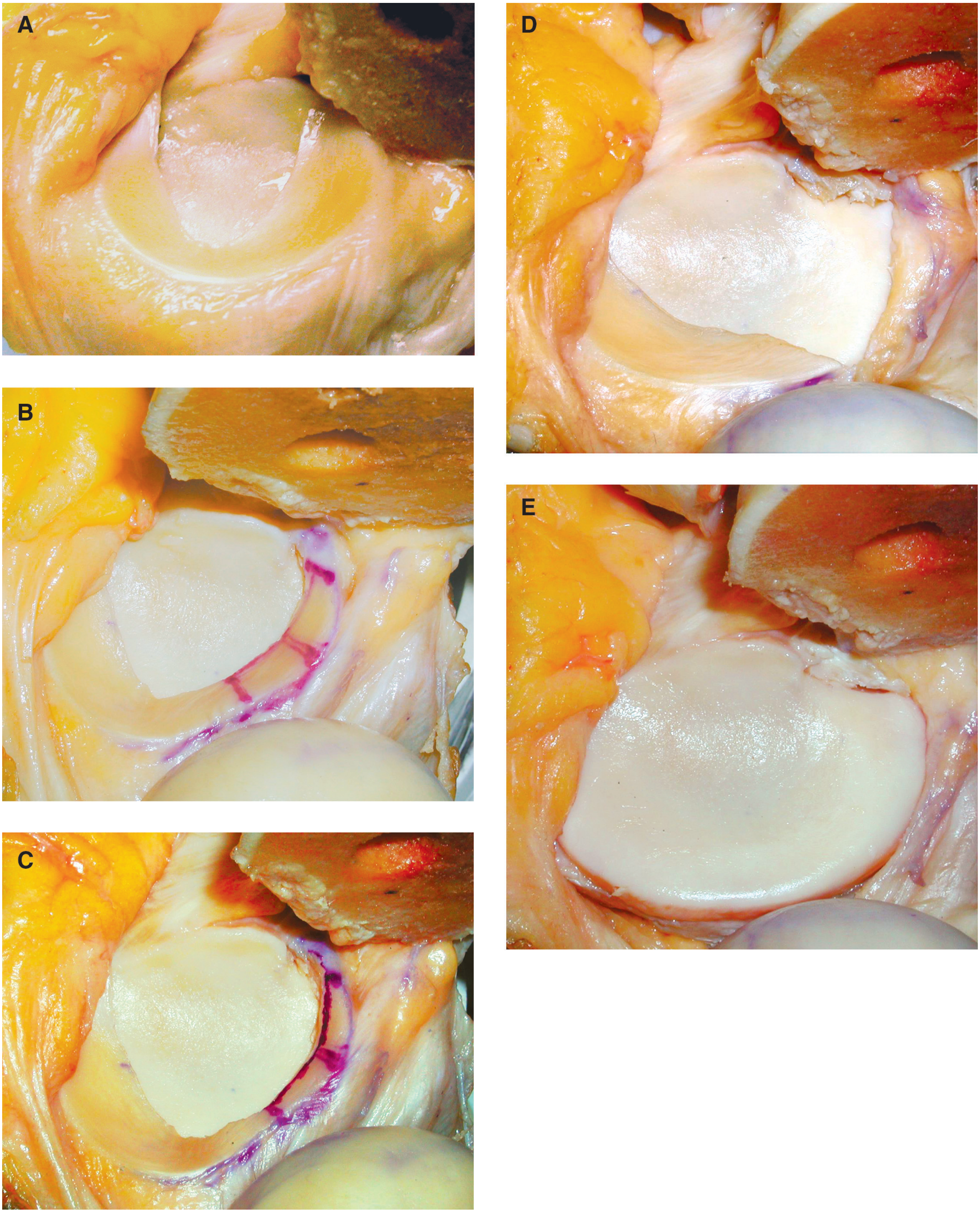

Figure 4. The medial compartment after undergoing the 5 posterior medial meniscectomy conditions. Intact medial meniscus (A), 50% radial width medial meniscectomy (B), 75% radial width medial meniscectomy (C), segmental medial meniscectomy (D), and total medial meniscectomy (E). Left = anterior.

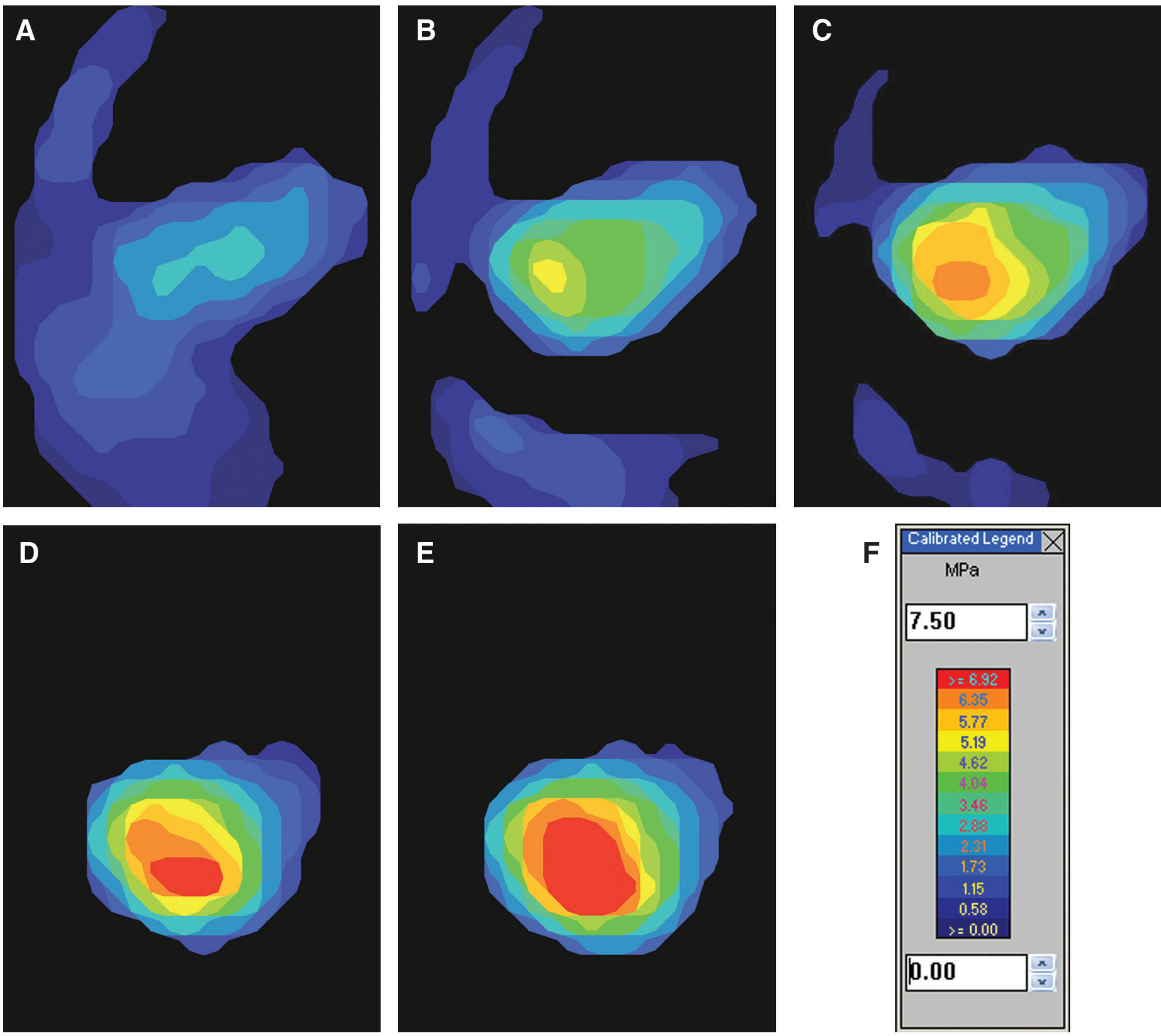

Figure 5. K-Scan 4000 contact area and stress maps representative of a specimen at 30° of flexion after undergoing the 5 posterior medial meniscectomy conditions. Intact medial meniscus (A), 50% radial width medial meniscectomy (B), 75% radial width medial meniscectomy (C), segmental medial meniscectomy (D), and total medial meniscectomy (E). Calibrated contact stress legend (F). Top = anterior.

medial meniscectomy simulating a meniscectomy extending into the red-red zone, (4) segmental medial meniscectomy, and (5) total medial meniscectomy (Figure 4). As the widths of menisci varied across specimens, we found it more accurate and reproducible to remove a defined percentage of radial width for each meniscectomy condition. The radial width of the posterior medial meniscus of the intact knee was measured at 3 separate locations: (1) posterior margin: 3 mm from the posterior horn, (2) anterior margin: 20 mm anteriorly from the posterior margin, and (3) at the midpoint between these 2 measurements. The meniscocapsular junction was used as the peripheral border of the medial meniscus. These points were delineated with a surgical marking pen to provide guidelines in performing subsequent meniscectomies. Each meniscectomy was performed using a No. 15 blade scalpel beginning 3 mm from the posterior horn and extending 20 mm anteriorly, approximately to the midline of the medial collateral ligament. Radial widths of the medial meniscus were measured before and after each meniscectomy condition to confirm that the correct amount of meniscus was removed. All meniscectomy conditions were tested under an axial load of 1800 N (approximately 2.5 times body weight for a 70-kg individual), chosen to approximate the load experienced by the knee during gait,[40] while knee flexion angles of 0°, 30°, and 60° were used to represent the typical range of motion during gait. Thus, each specimen underwent 15 separate testing conditions (5 meniscectomy conditions × 3 flexion angles). Our pilot studies demonstrated highly reproducible measurements using the K-Scan 4000 system. Multiple

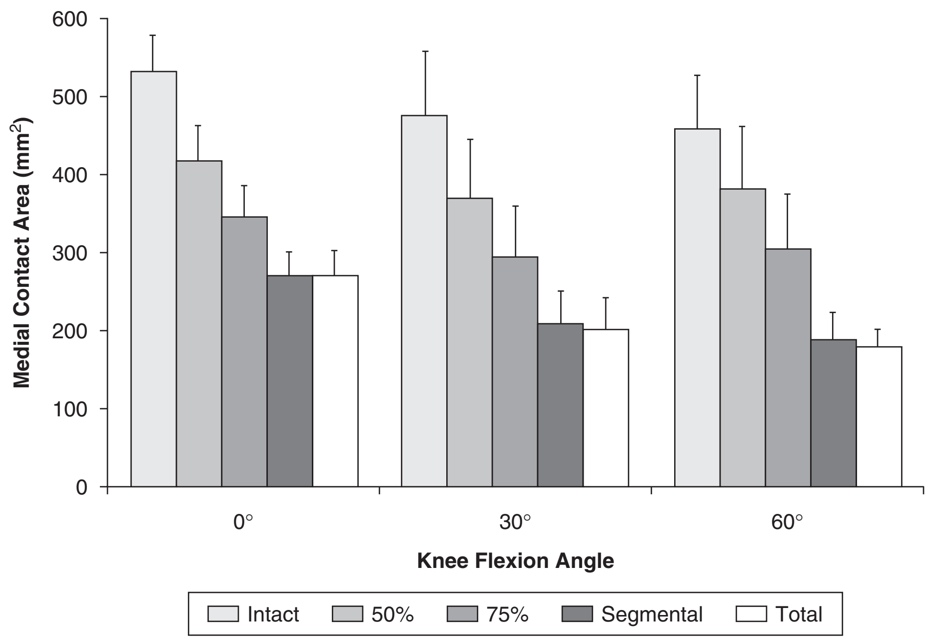

Figure 6. Medial contact areas for all posterior medial meniscectomy conditions at 0°, 30°, and 60° of flexion. Significant differences were noted between all meniscectomy conditions except between the segmental and total meniscectomy conditions. Error bars represent ± 1 SD.

TABLE 1
Incremental Percentage Change in Medial Contact Area for All Posterior Medial Meniscectomy Conditions at 0°, 30°, and 60° of Flexion

Meniscectomy Condition	0° of Flexion		30° of Flexion		60° of Flexion	
	Mean	SD	Mean	SD	Mean	SD
Intact-50%	–21.47	3.73	–22.00	5.55	–16.79	6.62
50%-75%	–17.16	2.80	–20.52	5.32	–20.05	7.72
75%-segmental	–21.84	5.05	–29.40	5.62	–37.93	12.18
Segmental-total	–0.04	1.61	–3.78	1.94	–5.88	2.31

measurements of a given knee for each testing condition resulted in a standard deviation of less than 5%, and thus only 1 measurement was taken under each testing condition to limit the effects of repetitive testing and wear on the knee specimens and sensors. Knee specimens were sprayed with a saline solution throughout the duration of testing to prevent desiccation.

The K-Scan 4000 software was used to generate a contact map of each knee (Figure 5) and measure total force, medial force, contact area (CA), mean contact stress (MCS), and peak contact stress (PCS). Within a given contact area, the knee experiences a range of contact stresses. Thus, PCS is measured to quantify the greatest stress experienced under each testing condition, whereas MCS represents an average of the stresses across the contact area. Erroneous stress peaks produced by sensor crinkling were adjusted by averaging the data from each sensel (sensing element) with its neighboring sensels. In addition, if any missing rows or columns of data existed, they were averaged from the adjacent rows or columns. These adjustments occurred in less than 5% of all measurements and did not result in any significant changes in the data presented.

Data Analysis

Statistical analysis was performed using SPSS 11.0 for Windows (SPSS Inc, Chicago, Ill). A 1-way analysis of variance (ANOVA) with a Bonferroni adjustment for multiple comparisons was used to evaluate differences in CA, MCS, and PCS among the 5 posterior medial meniscectomy conditions. Where significant differences were indicated, paired comparisons were made using the Tukey method. $P < .05$ was considered statistically significant.

RESULTS

The mean total force did not significantly differ across flexion angles or meniscectomy conditions ($P > .17$). The mean medial force distribution varied from 51% to 35% to 41% of the total force at 0°, 30°, and 60° ($P < .05$), respectively, but showed no significant differences across meniscectomy conditions ($P > .93$). One specimen failed because of an ACL rupture while testing at the 75% meniscectomy condition, resulting in data only for the intact and 50% meniscectomy conditions for this specimen.

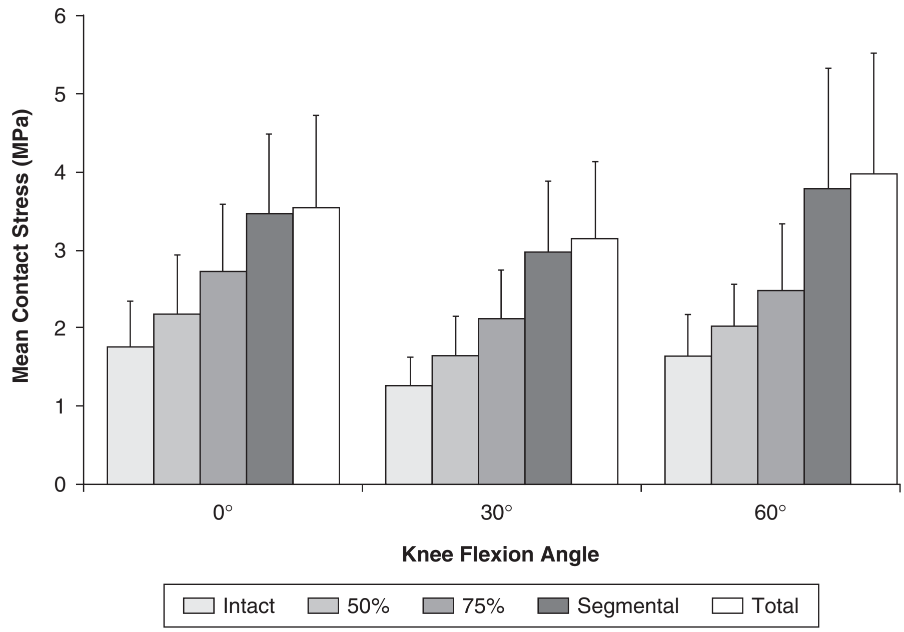

Figure 7. Medial mean contact stress for all posterior medial meniscectomy conditions at 0°, 30°, and 60° of flexion. Significant differences were noted between all meniscectomy conditions except between the segmental and total meniscectomy conditions. Error bars represent ± 1 SD.

TABLE 2
Incremental Percentage Change in Medial Mean Contact Stress for All Posterior Medial Meniscectomy Conditions at 0°, 30°, and 60° of Flexion

Meniscectomy Condition	0° of Flexion		30° of Flexion		60° of Flexion	
	Mean	SD	Mean	SD	Mean	SD
Intact-50%	23.28	6.46	28.35	12.65	21.38	11.64
50%-75%	25.21	9.46	27.96	11.83	22.53	13.37
75%-segmental	27.34	8.24	40.43	10.25	52.76	31.00
Segmental-total	2.16	3.90	6.07	3.84	5.37	2.46

Medial Contact Area

Medial CA data are presented for each posterior medial meniscectomy condition at 0°, 30°, and 60° (Figure 6). The medial CA in the intact knee was 533 mm^2, 477 mm^2, and 460 mm^2, respectively. Compared with the intact state, medial CA decreased 20% (50% meniscectomy), 35% (75% meniscectomy), 53% (segmental meniscectomy), and 54% (total meniscectomy). Significant differences in medial CA were noted between all posterior medial meniscectomy conditions ($P < .05$) except between the segmental and total meniscectomy conditions.

Data representing the incremental percentage change in medial CA are presented in Table 1. Similar incremental changes in medial CA were seen between the intact-to-50% and 50%-to-75% meniscectomy conditions across all flexion angles. For the 75%-to-segmental condition, the incremental changes in medial CA seen at 30° and 60° of flexion were significantly larger than that at 0°.

Medial Mean Contact Stress

Medial MCS data are presented for each posterior medial meniscectomy condition at 0°, 30°, and 60° (Figure 7). The medial MCSs in the intact knee were 1.77 N, 1.29 N, and 1.66 N, respectively. Each progressive meniscectomy condition increased medial MCS compared with the intact state: 24% (50% meniscectomy), 58% (75% meniscectomy), 128% (segmental meniscectomy), and 134% (total meniscectomy). Significant differences in medial MCS were noted between all posterior medial meniscectomy conditions ($P < .05$) except between the segmental and total meniscectomy conditions.

Data representing the incremental percentage change in medial MCS are presented in Table 2. Similar incremental changes in medial MCS were seen between the intact-to-50% and 50%-to-75% meniscectomy conditions across all flexion angles. For the 75%-to-segmental condition, the incremental changes in medial MCS seen at 30° and 60° of flexion were significantly larger than at 0°.

Medial Peak Contact Stress

Medial PCS data are presented for each posterior medial meniscectomy condition at 0°, 30°, and 60° (Figure 8). The medial PCSs in the intact knee were 4.47 N, 3.10 N, and 4.35 N, respectively. Compared with the intact state, medial PCS increased 43% (50% meniscectomy), 95% (75% meniscectomy), 123% (segmental meniscectomy), and 136% (total meniscectomy). Significant differences in medial PCS were noted between all posterior medial meniscectomy

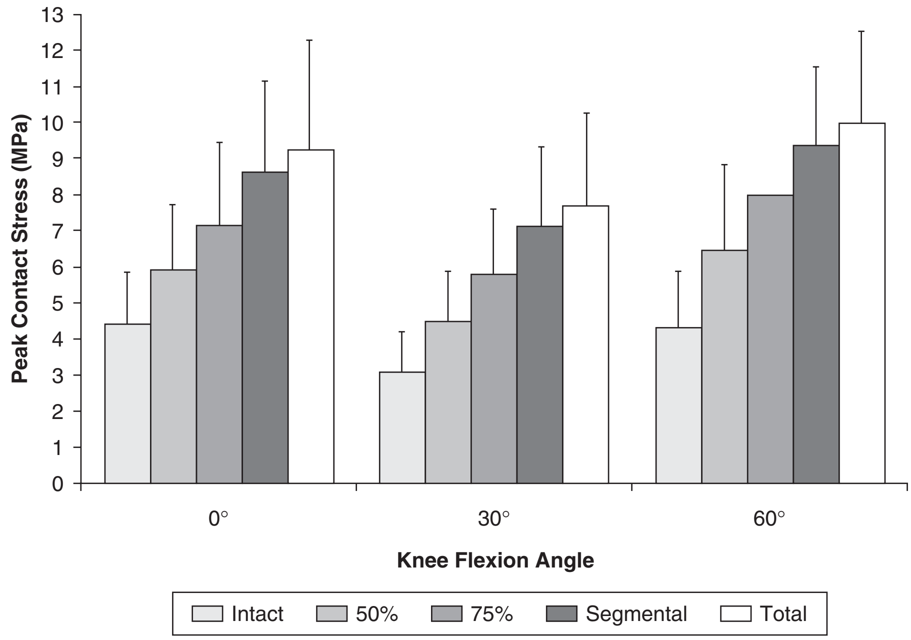

Figure 8. Medial peak contact stress for all posterior medial meniscectomy conditions at 0°, 30°, and 60° of flexion. Significant differences were noted between all meniscectomy conditions except between the segmental and total meniscectomy conditions. Error bars represent ± 1 SD.

TABLE 3
Incremental Percentage Change in Medial Peak Contact Stress for All Posterior Medial Meniscectomy Conditions at 0°, 30°, and 60° of Flexion

Meniscectomy Condition	0° of Flexion		30° of Flexion		60° of Flexion	
	Mean	SD	Mean	SD	Mean	SD
Intact-50%	32.95	11.31	45.42	20.86	48.69	8.28
50%-75%	20.63	3.93	25.32	10.65	23.59	9.13
75%-segmental	20.80	10.64	22.11	7.84	17.50	4.99
Segmental-total	7.05	3.17	8.56	2.11	6.74	3.89

conditions ($P < .05$) except between the segmental and total meniscectomy conditions.

Data representing the incremental percentage change in medial PCS are presented in Table 3. The incremental change in medial PCS from the intact-to-50% meniscectomy condition was 1.5 to 2 times greater than that from the 50%-to-75% meniscectomy condition across all flexion angles. Similar incremental changes in medial PCS were seen between the 50%-to-75% and 75%-to-segmental meniscectomy conditions.

DISCUSSION

Methodological Issues

The K-Scan sensor was chosen for this study because it offers the advantages of simplicity, reproducibility, ability to capture dynamic measurements, and reusability.[16,22] Harris et al[22] reported the contact area and stress measurements from these sensors to be more reliable and reproducible than those from Fuji film. The direct computer interface allows for real-time data acquisition in the form of a snapshot or movie as testing conditions are varied. The software package enables the user to adjust for missing rows or columns of data by extrapolating from neighboring rows and columns and to edit out false pressure “spikes” caused by sensor crinkling. A single sensor can be used for several measurements throughout a variety of testing configurations, resulting in decreased trauma from repeated insertion and removal, as is required with Fuji film. However, the K-Scan sensor is not without its limitations. Although the sensor is thin (0.1 mm), it represents a finite thickness that may alter contact area and stress measurements (but it is still thinner than Fuji film [0.25-1.0 mm]). It is sensitive to temperature changes and needs to be calibrated at the ambient temperature experienced during testing, as does Fuji film. Although the sensor is reusable, its lifetime is greatly reduced under severe loading conditions. The K-Scan sensor is available in a variety of shapes; however, it cannot simply be cut to the desired specifications as with Fuji film. Custom-designed sensors are available through the manufacturer but remain a costly option.

Comparison With Prior Studies

To the authors’ knowledge, there have been no studies evaluating the change in tibiofemoral contact mechanics after defined serial posterior medial meniscectomies.

Two prior studies have evaluated the effects of partial meniscectomy; Baratz et al[7] tested 3 knees with a 33% radial width meniscectomy along the entire length of the medial meniscus, while Ihn et al[25] tested 2 knees after undergoing an undefined partial medial meniscectomy. Comparisons between studies are complicated by differing experimental conditions and methods for measuring knee contact mechanics. Nevertheless, general comparisons can be made to previous studies regarding the relative changes in contact mechanics following medial meniscectomy.

Our study confirms the observation that the meniscus participates in load transmission in the knee, as each progressive posterior medial meniscectomy condition resulted in decreasing CA and increasing MCS and PCS in comparison with the intact knee. After a partial medial meniscectomy, Baratz et al[7] and Ihn et al[25] reported a 5% to 10% and a 20% decrease in CA, respectively. These values correlate with our CA measurements obtained after a 50% posterior medial meniscectomy. The decrease in CA after total meniscectomy in our study is consistent with those of Ahmed and Burke[2] (50%-70%) and Ihn et al[25] (40%), but it is slightly lower than that reported by Baratz et al[7] (75%). The increase in MCS after total meniscectomy in our study is in agreement with those of Krause et al[34] (141%) and Kurosawa et al[35] (140%). Baratz et al[7] reported a 40% to 60% increase in PCS after partial medial meniscectomy, which is in agreement with our PCS measurements after 50% posterior medial meniscectomy. In addition, the increase in PCS after total medial meniscectomy in our study falls well within the of range of values reported in previous studies (15%-450%).[2,7,12,20,46,51]

Contact Mechanics

A linear relationship between the degree of medial meniscectomy and medial CA and MCS would have resulted in incremental changes from the intact-to-50% meniscectomy condition to be twice as large as that from the 50%-to-75% meniscectomy condition. Similar incremental changes in medial CA and MCS between the intact-to-50% condition and 50%-to-75% condition suggest the presence of a nonlinear relationship between the degree of meniscectomy and CA and MCS. This result indicates that the peripheral region of the medial meniscus plays a greater role in increasing CA and decreasing MCS compared with the central region. By contrast, the medial PCS data demonstrate a nearly linear relationship between the degree of meniscectomy and PCS, as the incremental change between the intact-to-50% meniscectomy condition is approximately twice that of the 50%-to-75% meniscectomy condition. This finding suggests that PCS increases proportionally to the amount of meniscus removed.

Greater incremental changes in medial CA and MCS were found for the 75%-to-segmental meniscectomy condition at 30° and 60° of flexion compared with that at 0°, as the increasing flexion angle resulted in posterior translation of the contact area along the tibial plateau. This finding is not surprising, as the effects of segmental posterior medial meniscectomy would be expected to be more prominent as the area of tibiofemoral contact moves posteriorly along the tibial plateau and loses contact with the remaining anterior portion of the medial meniscus.

Radial tears extending to the periphery[52] and meniscal allograft transplants without fixation of the anterior and posterior horns[3,4,45] result in the loss of hoop tension and have been shown to be equivalent to total meniscectomy in load-bearing terms. A segmental meniscectomy is another setting in which hoop tension is compromised. This effect was visualized by the extrusion of the anterior remnant of the medial meniscus during testing, supporting the concept that a segmental meniscectomy results in a biomechanical state similar to total meniscectomy. Our study revealed no significant differences in CA, MCS, or PCS between segmental and total medial meniscectomy conditions.

Limitations

One limitation of our study was the lack of freedom of the varus/valgus moment in the knee specimen setup. Every effort was made to ensure there was no preferential overloading between the medial and lateral compartments by creating the femoral tunnels and potting the tibial plateau parallel to the testing surface. However, the percentage of the axial load borne by the medial compartment varied from 51% at 0° to 35% at 30° to 41% at 60°. An option to adjust the varus/valgus moment on the femoral jig would have allowed for an equal load split between the medial and lateral compartments throughout all flexion angles, likely resulting in slightly larger CA and significantly larger MCS and PCS at 30° and 60°. Despite this deficiency, the conclusions of this study remain valid, as the main objective was to determine the biomechanical effects of the 5 serial medial meniscectomy conditions rather than a comparison of these effects across varying knee flexion angles.

Another limitation of our study is that a single measurement was taken for each testing condition. This procedure was done to minimize the effects of repetitive manipulation, testing, and wear on the knee specimens and sensors. Although a prior study by Harris et al[22] and our own pilot study demonstrated the high accuracy and reproducibility of measurements using the K-Scan sensors, it would have been preferable to obtain 3 readings for each testing condition to increase the precision of the measurements.

Clinical Implications

Whether degenerative changes in the articular surfaces of the knee are primarily related to increased PCS or decreased CA and the resulting increased MCS is of clinical interest. It has been shown that articular damage initially occurs in the areas of direct tibiofemoral contact where PCS is the greatest.[9,13,33] Thus, it is likely that increased PCS rather than decreased CA and increased MCS is mainly responsible for degenerative changes in the articular surface of the knee. Our results reveal that PCS increases proportionally to the degree of medial meniscectomy. This finding supports the argument for preservation of as much of the meniscus as possible in treating meniscal injuries.

Future studies correlating biomechanical findings to clinical outcomes will be of great interest.

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