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Dynamic Contact Mechanics of the Medial Meniscus as a Function of Radial Tear, Repair, and Partial Meniscectomy

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Background: The menisci are integral to normal knee function. The purpose of this study was to measure the contact pressures transmitted to the medial tibial plateau under physiological loads as a function of the percentage of the meniscus involved by the radial tear or repair. Our hypotheses were that (1) there is a threshold size of radial tears above which contact mechanics are adversely affected, and (2) partial meniscectomy results in increased contact pressure compared with that found after meniscal repair.

Methods: A knee simulator was used to apply physiological multidirectional dynamic gait loads across human cadaver knees. A sensor inserted below the medial meniscus recorded contact pressures in association with (1) an intact meniscus, (2) a radial tear involving 30% of the meniscal rim width, (3) a radial tear involving 60% of the width, (4) a radial tear involving 90% of the width, (5) an inside-out repair with horizontal mattress sutures, and (6) a partial meniscectomy. The effects of these different types of meniscal manipulation on the magnitude and location of the peak contact pressure were assessed at 14% and 45% of the gait cycle.

Results: The peak tibial contact pressure in the intact knees was 6 ± 0.5 MPa and 7.4 ± 0.6 MPa at 14% and 45% of the gait cycle, respectively. The magnitude and location of the peak contact pressure were not affected by radial tears involving up to 60% of the meniscal rim width. Radial tears involving 90% resulted in a posterocentral shift in peak-pressure location manifested by an increase in pressure in that quadrant of 1.3 ± 0.5 MPa at 14% of the gait cycle relative to the intact condition. Inside-out mattress suture repair of a 90% tear did not restore the location of the pressure peak to that of the intact knee. Partial meniscectomy led to a further increase in contact pressure in the posterocentral quadrant of 1.4 ± 0.7 MPa at 14% of the gait cycle.

Conclusions: Large radial tears of the medial meniscus are not functionally equivalent to meniscectomies; the residual meniscus continues to provide some load transmission and distribution functions across the joint.

Clinical Relevance: The results of this study support meniscal preservation and repair of medial radial tears.

The menisci are integral to normal knee joint function and play an important role in joint lubrication, load distribution, joint stability, and proprioception. The wedge-shaped menisci increase the congruity between the convex femur and the relatively flat tibia and thereby protect the articular cartilage from excessive axial loads[1-10]. Radial meniscal tears are not uncommon in young patients[11], and they often occur at the junction of the body and the posterior horn of the medial meniscus. The treatment of radial meniscal tears is directed at the prevention of future degenerative disease through meniscal preservation whenever feasible[12-14]. Historically, radial tears extending to the periphery have been believed to result in the reduction of meniscal hoop strength and have been described as functionally equivalent to a total meniscectomy[15]. For this reason, partial meniscectomy—the removal of the damaged, unstable portion of the meniscus—has been the mainstay of surgical treatment. Although the classic teaching has been that only peripheral and longitudinal tear patterns will heal after

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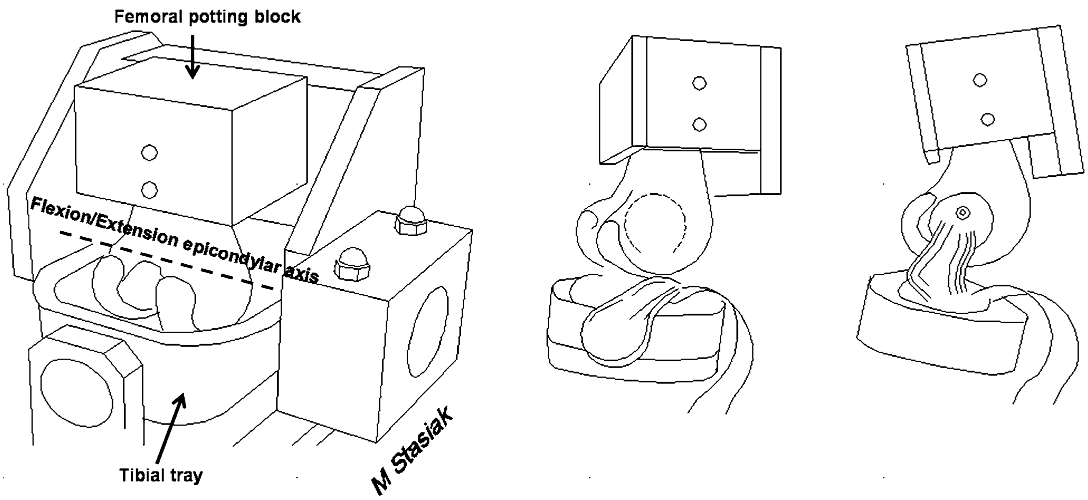

Fig. 1

Left: Schematic of a human cadaver knee mounted in the Stanmore knee simulator. The posterior femoral condyles are visible. *Middle:* Prior to testing, the knee was removed from the loading station and an osteotomy at the site of the insertion of the medial collateral ligament on the medial femoral condyle was performed. *Right:* The osteotomy site was rigidly fixed between test conditions with a 50-mm-long, 3.5-mm-diameter cortical screw. (Printed with permission of Mark E. Stasiak.)

reduction and repair, it is now clear that other tear configurations may heal if given the opportunity by adequate preparation of the meniscal rim, careful suturing, and biological augmentation of healing[16,17]. It is unclear if there is a "critical size" of radial tears of the medial meniscus that precipitates biomechanically deleterious effects in the ipsilateral compartment. Such information would help to identify those tears that merit a suture repair.

Experimental models offer the opportunity to assess the effect of radial tears and repair on the contact mechanics of the knee. Indeed, degenerative changes associated with meniscectomies have been linked to increased joint contact stress (hereafter referred to as *contact pressure*) in the adjacent articular cartilage as measured in vitro[18-27]. To date, however, experimental models have been primarily conducted under static or quasi-static uniaxial loading conditions[8,28-33]. Given the sensitivity of joint contact pressures to the magnitude and direction of an applied load[34,35], these models do not accurately capture the physiological effect of meniscal repair or meniscectomy on knee contact mechanics. This challenges our ability to evaluate the potential effect of meniscal tears and repair techniques on joint contact mechanics.

The purpose of this study was to measure the contact pressures transmitted to the medial tibial plateau under dynamic physiological loads as a function of the percentage of the meniscus involved by the radial tear or repair. Our hypotheses were that (1) there is a threshold size of radial tears above which contact mechanics are adversely affected, and (2) partial meniscectomy results in increased mean and peak contact pressures compared with those found after meniscal repair. To test these hypotheses, the pressure magnitude, location, and profile, as distributed across the tibial plateau of human cadaver knees, were quantitatively assessed during simulated gait.

Materials and Methods

Approval for use of cadaver specimens was granted by our institutional review board. A four-station load-controlled Stanmore KC Knee Joint Simulator (University College London, Middlesex, United Kingdom) traditionally used to measure wear of polyethylene total knee replacement components[36,37] was utilized for this experiment. The apparatus is designed so that the femoral component rotates about a fixed, predefined flexion/extension axis, while the tibia can move in six degrees of freedom, which has been shown to allow physiological movement of total joint replacement components[38] and of cadaver knees under gait loading conditions[39]. The simulator can be programmed to simultaneously and dynamically control the axial force, anterior force, posterior force, and rotational moment (internal/external torque), as a function of the applied flexion-extension angle profile, applied to a specimen.

The number of specimens was determined by performing a power analysis of the peak contact pressure on the tibial plateau of four intact knees. We powered the study to detect a 25% increase in peak contact pressure in the presence of a meniscal radial tear[31], with a power of 80% and an alpha of 0.05. The analysis revealed that a sample size of eight was required to demonstrate significance. Therefore, eight fresh-frozen cadaver knees devoid of any ligamentous or meniscal injury were obtained from female donors (mean age, 61.25 years; range, fifty-seven to sixty-eight years). Skin, subcutaneous fat, muscle, and the patella were removed, with care taken to preserve the cruciate ligaments, collateral ligaments, and capsule. The femur and tibia were then transected approximately 10 cm above and below the joint line, respectively. Under fluoroscopy, a 2.5-mm Kirschner wire was drilled along the epicondylar axis parallel to the joint line. Anteroposterior

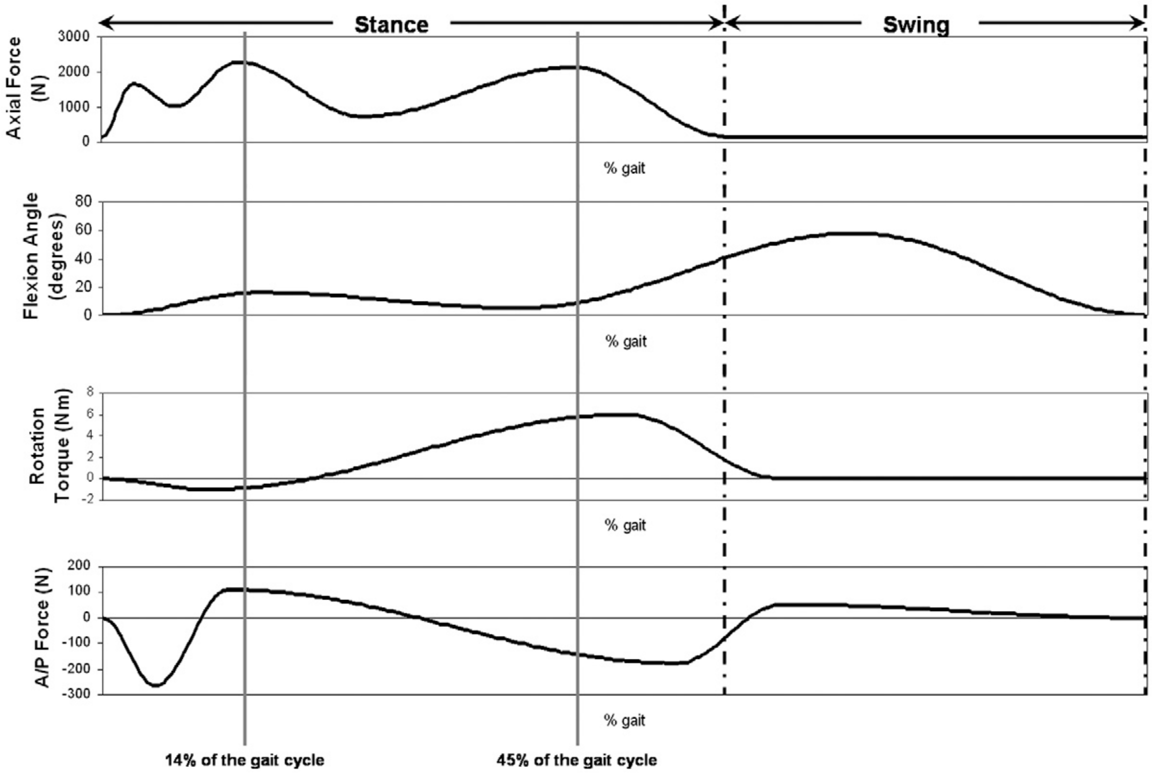

Fig. 2

Simulator inputs as a function of the percentage of the gait cycle over one loading cycle. The top graph is the axial force loading profile, with identification of the two most prominent peaks in stance, which occur at 14% and 45% of the gait cycle. The bottom three graphs show the input variables of flexion angle (in degrees), rotation torque (in newton-meters), and anterior/posterior (A/P) force (in newtons) provided to the simulator to reproduce normal gait kinematics of the knee.

and lateral fluoroscopic images were obtained to confirm the accuracy of pin placement. With the knee suspended by means of the transepicondylar wire along the axis of rotation of the simulator, the tibia was centered in the base of the simulator and aligned such that the plateau was parallel to the ground in full extension. (It should be noted that the ability to reproducibly

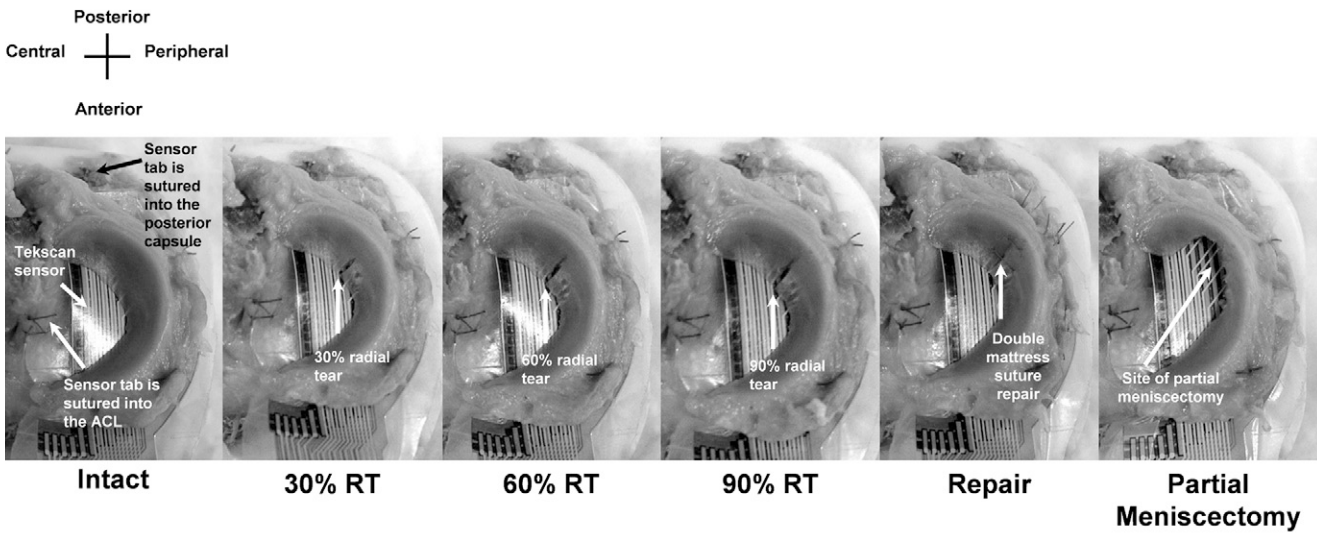

Fig. 3

Representative images illustrating the sequential surgical manipulations of the meniscus. The sensor was attached with use of tabs to the anterior cruciate ligament (ACL) and to the posteroinferior aspect of the capsule. Note that the femur was removed for illustrative purposes only. RT = radial tear.

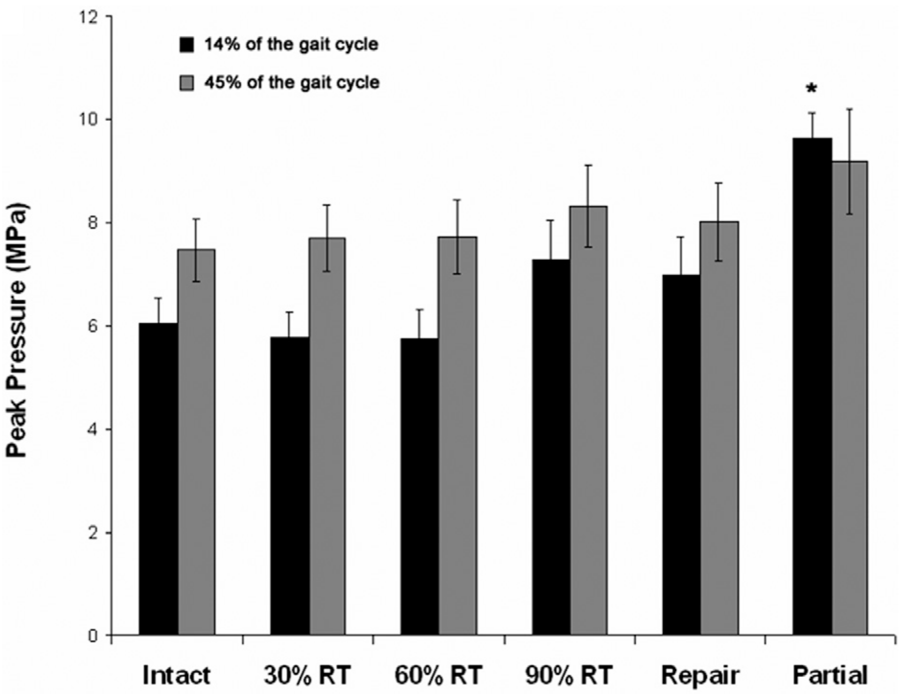

Fig. 4-A

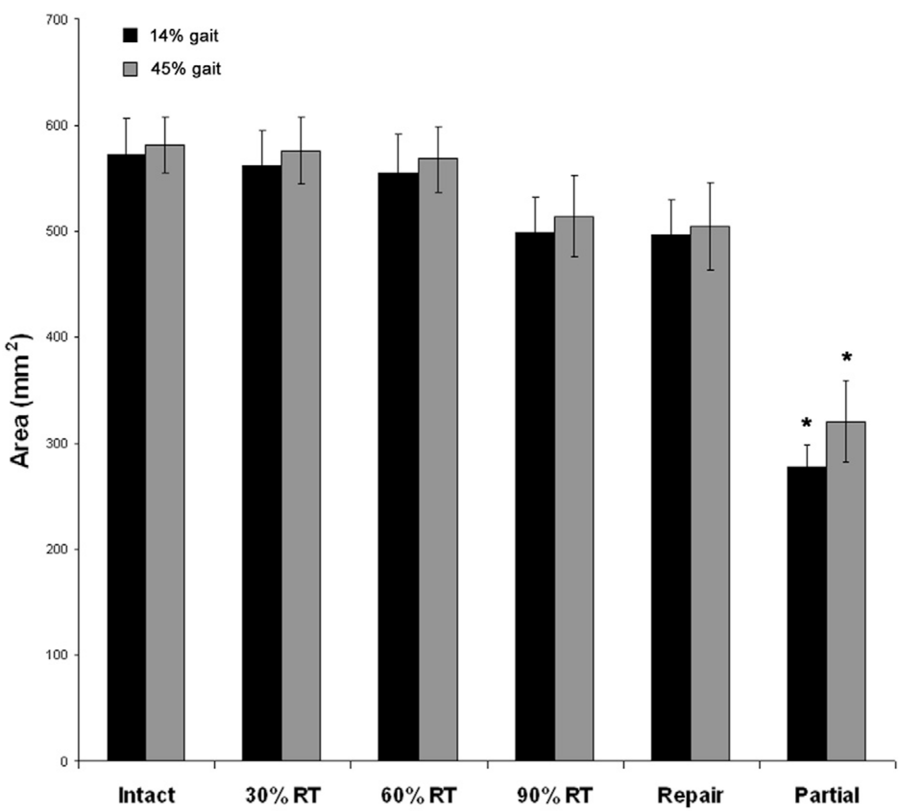

Fig. 4-B

Peak contact pressure (Fig. 4-A) and contact area (Fig. 4-B) across the entire sensor under each condition at 14% and 45% of the gait cycle. The bars and I bars represent the mean and standard deviation. *$p < 0.05$. RT = radial tear.

identify and align the epicondylar axis of each femur was crucial for ensuring physiological motions of the knee joint.) The tibia-fibula complex and the femur were potted into fixtures with polymethylmethacrylate bone cement (Fig. 1, *left*). After the cement was cured, the knee was removed from the loading station and an osteotomy at the site of the insertion of the medial collateral ligament on the medial femoral condyle was performed to reproducibly provide repeated access into

TABLE I Mean Contact Pressure Across the Entire Medial Plateau for Each Test Condition at 14% and 45% of the Gait Cycle*

	Mean Contact Pressure *(MPa)*	
Test Condition	14% of Gait Cycle	45% of Gait Cycle
Intact	1.49 ± 0.07	1.68 ± 0.10
30% radial tear	1.5 ± 0.08	1.67 ± 0.14
60% radial tear	1.47 ± 0.10	1.66 ± 0.16
90% radial tear	1.66 ± 0.15	1.91 ± 0.21
Inside-out horizontal mattress repair	1.59 ± 0.13	1.87 ± 0.21
Partial meniscectomy	3.05 ± 0.14†	2.76 ± 0.28†

*The values are given as the mean and standard deviation. †The mean contact pressure after the partial meniscectomy was significantly higher than the values under all other test conditions at both 14% and 45% of the gait cycle ($p < 0.01$).

the medial compartment without compromising the medial collateral ligament complex (Fig. 1, *middle*). The osteotomy site was rigidly fixed between test conditions with a 50-mm-long, 3.5-mm-diameter cortical screw (Fig. 1, *right*). Pilot work that involved testing and retesting of an intact knee indicated that the osteotomy led to a change in peak contact pressure of approximately 5%; this observation is similar to that reported by Lee et al.[28] and by Martens et al.[40], who found that such an osteotomy had little effect on measured joint contact pressure.

The pressures transmitted to the tibial plateau were measured with use of an array of piezoelectric pressure-sensing elements contained within a thin sealed sheet of plastic (4010N; Tekscan, South Boston, Massachusetts)[41,42]. Each sensor was placed between two layers of Tegaderm adhesive dressing (3M, Minneapolis, Minnesota) to avoid any fluid seepage into the sensor. Plastic augment tabs were fixed along the edges of the sensor to allow suture fixation. Each sensor was conditioned, equilibrated, and calibrated according to the manufacturer's instructions[43]. One-centimeter incisions were made in the meniscotibial (coronary) ligaments anteriorly and posteriorly in line with their fibers, allowing the sensor to be passed beneath the medial meniscus and flush with the tibial plateau without detaching the meniscotibial ligaments, meniscofemoral ligaments, or their capsular attachments. The sensor was secured with multiple figure-of-eight 3-0 Ethibond sutures (Ethicon, Somerville, New Jersey) placed through the tibial insertion of the anterior cruciate ligament and the posteroinferior aspect of the knee capsule. Sensor security was tested manually and with precycling on the load-controlled simulator to ensure that there was no shift in its position

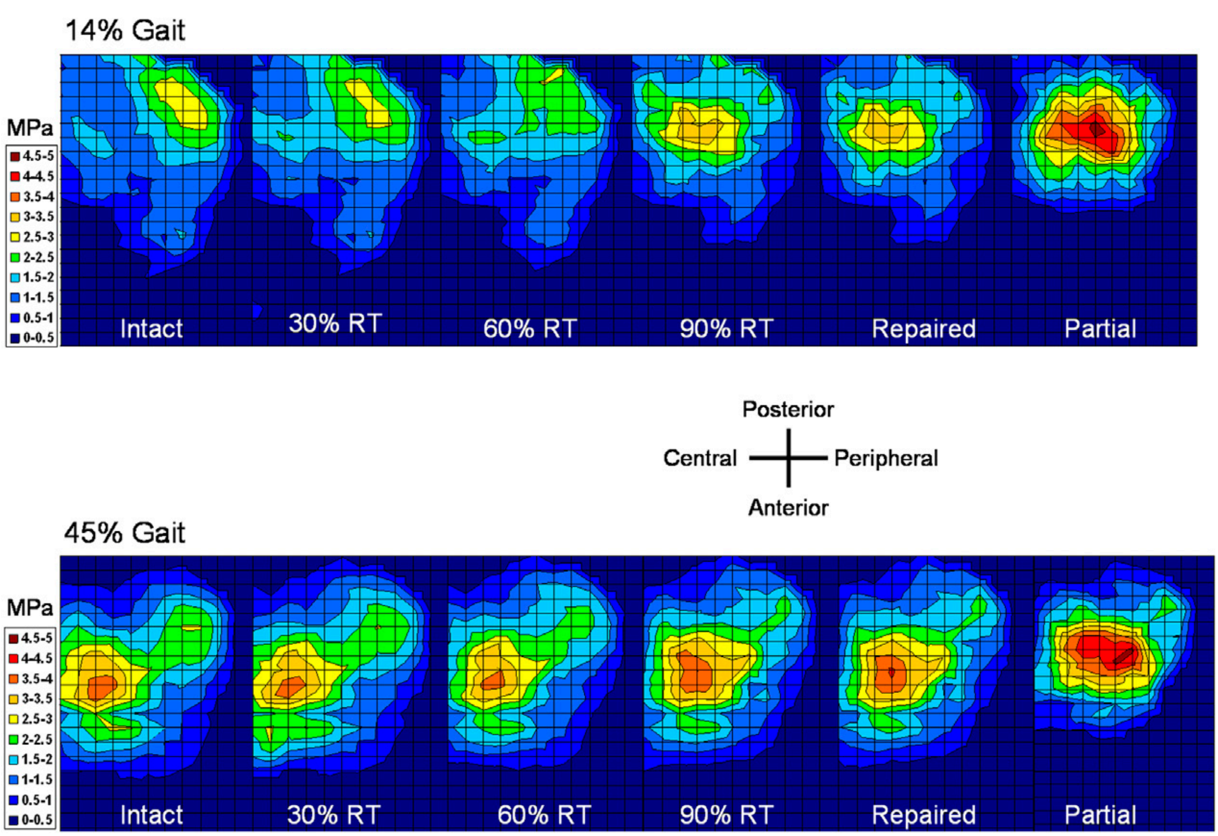

Fig. 5

Pressure distribution averaged across the eight knees as a function of meniscal manipulation at 14% and 45% of the gait cycle. RT = radial tear.

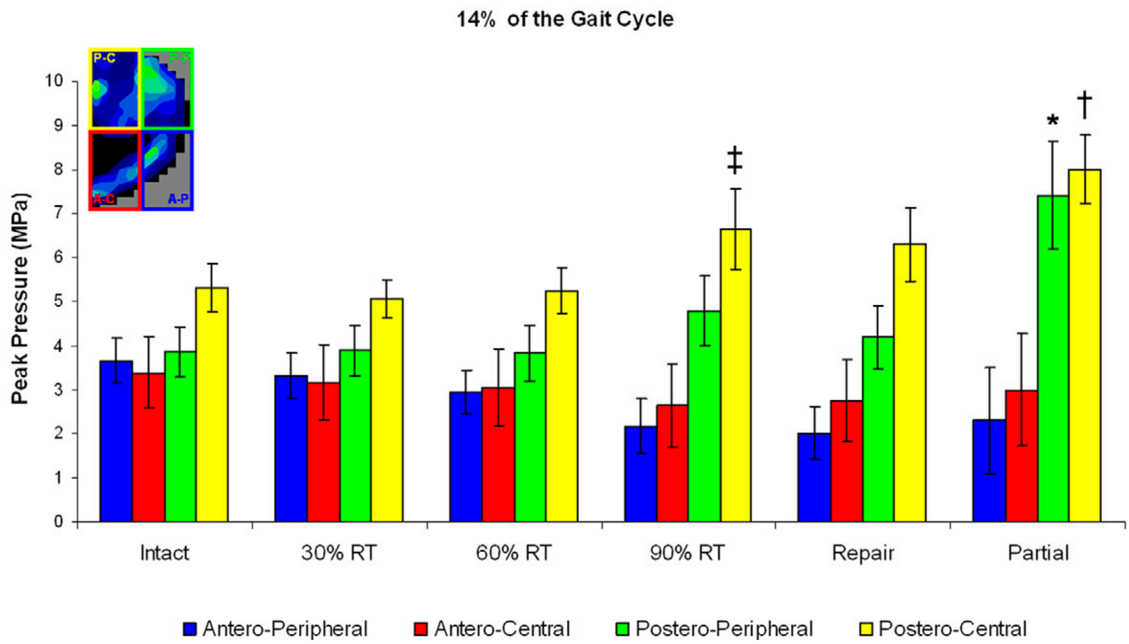

Fig. 6-A

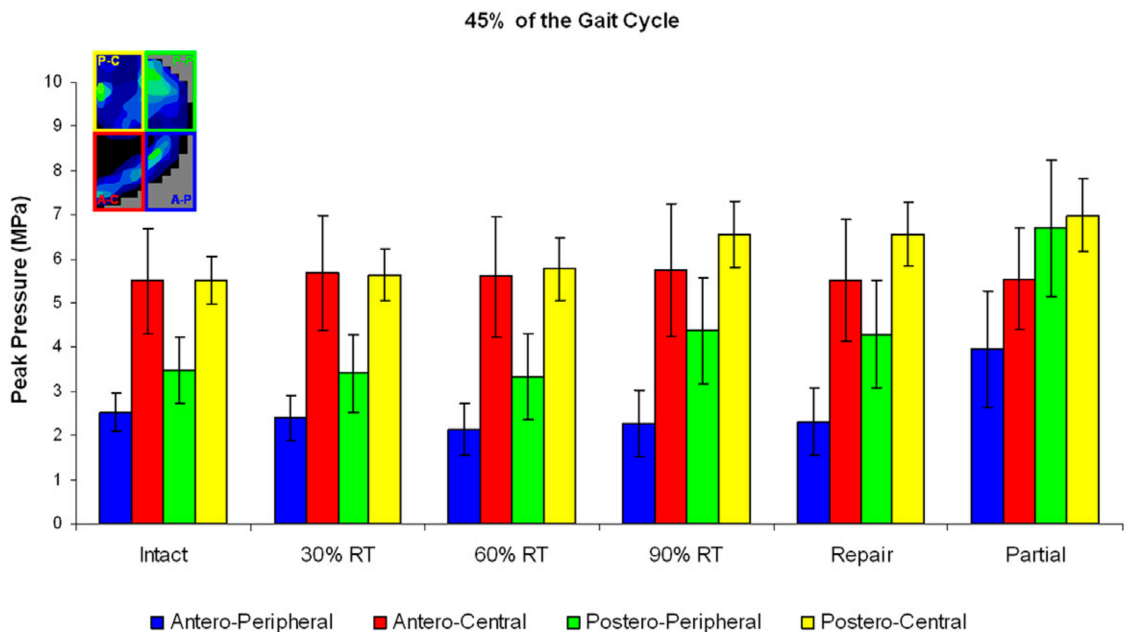

Fig. 6-B

The magnitude of peak contact pressure in each of the four quadrants under each test condition at 14% (Fig. 6-A) and 45% (Fig. 6-B) of the gait cycle. *,†A significant increase in peak pressure when compared with all other conditions. ‡A significant increase in peak pressure when compared with the intact, 30% radial tear, and 60% radial tear conditions. The images in the upper left side of each figure illustrate the quadrants as defined from the sensor placed on the medial tibial plateau. A-P = anteroperipheral, A-C = anterocentral; P-P = posteroperipheral, and P-C = posterocentral. RT = radial tear. The bars and I bars represent the mean and standard deviation.

within or between test conditions. The pressure sensor was programmed to record data at 9.5 Hz, which was the maximum frequency allowed by the system.

The inputs to the simulator (axial force, flexion-extension, rotational torque, and anterior/posterior force profile) were based on the guidelines of the International Organization for Standardization (ISO number 14243-1), which documents the forces required to simulate gait on the basis of data extracted from telemetry findings for patients with total knee replacement[44]. The two most pronounced peaks in axial force during the stance phase of gait—peak 1, which occurred at 14% of the gait cycle and at 15° of knee flexion, and peak 2,

TABLE II Contact Area in Each of the Four Quadrants for Each Test Condition at 14% and 45% of the Gait Cycle*

	Contact Area *(mm²)*			
	Anteroperipheral		Anterocentral	
Test Condition	14% of Gait Cycle	45% of Gait Cycle	14% of Gait Cycle	45% of Gait Cycle
Intact	100.19 ± 12.56	111.88 ± 10.74	110.13 ± 12.72	160.38 ± 18.08
30% radial tear	97.44 ± 12.16	108.5 ± 10.48	101.19 ± 13.13	155.38 ± 19.67
60% radial tear	94.56 ± 11.67	99.94 ± 10.57	97.06 ± 13.14	147.25 ± 21.23
90% radial tear	90.38 ± 12.53	94.56 ± 14.47	81.75 ± 14.74	130.06 ± 22.04
Inside-out horizontal mattress repair	87.31 ± 12.53	91.38 ± 16.09	82.5 ± 13.51	135.5 ± 23.19
Partial meniscectomy	36.75 ± 9.73†	59.38 ± 13.51†	27.06 ± 12.09†	83.81 ± 19.43†

*The values are given as the mean and standard deviation. †The contact area after the partial meniscectomy was significantly reduced compared with the values under all other test conditions in all quadrants at both 14% and 45% of the gait cycle ($p < 0.01$).

which occurred at 45% of the gait cycle and at 8° of knee flexion—were identified as targets for evaluation of joint contact pressures (Fig. 2). Precompressed anteroposterior springs (spring constant = 14.5 N/mm[39]) used to mimic soft-tissue constraints during wear testing were left intact. The simulator was programmed to apply twenty gait cycles at a frequency of 0.5 Hz.

Each of the following test conditions was modeled (Fig. 3): (1) the intact meniscus, (2) a radial tear involving 30% of the meniscal rim width, (3) a radial tear involving 60% of the width, (4) a radial tear involving 90% of the width, (5) an inside-out repair with horizontal mattress sutures, and (6) a partial meniscectomy. The radial tears were consistently created at the junction between the body and the posterior horn[14] with use of a number-15 blade. The radial width of each meniscus was measured at this location with use of a digital caliper device with the meniscocapsular junction defining its peripheral border. The 30%, 60%, and 90% tear widths were premarked with a surgical pen to provide guidelines for the transection distance for each test condition. The partial meniscectomy consisted of minimal adjacent resection to the width of the 90% radial tear with use of a number-15 blade and an arthroscopic resection biter device (Arthrex, Naples, Florida) with smooth contouring of the adjacent edges. Knee specimens were moistened with saline solution for the duration of testing to prevent tissue desiccation.

Data Analysis

The data set representing the pressure at each sensing element across the sensor from each test was output to Excel (Microsoft, Redmond, Washington) for analysis. The pressures at all sensing elements were averaged both at 14% and at 45% of the gait cycle for each condition across all eight knees. These data were used to produce colorimetric plots to act as a visual guide for the change in pressure profile as a function of meniscal status. The data were then analyzed to extract peak contact pressure, contact area, and mean contact pressure across each sensor at 14% and 45% of the gait cycle. The values for the last eight gait cycles for each test were averaged[43]. The sensor was then virtually divided into quadrants—anteroperipheral, anterocentral, posteroperipheral, and posterocentral. This analysis allowed identification of quadrant-specific changes in the location and magnitude of pressure as a function of meniscal manipulation.

Statistical analysis was performed with use of SAS 9.1.3 for Windows (Cary, North Carolina). A generalized estimating equations method with Bonferroni adjustment for multiple comparisons was used to evaluate differences between multiple test conditions and quadrants. The significance level was set at $p < 0.05$.

Source of Funding

Funding was received from the Widgeon Point Foundation, the Leo Rosner Foundation, and the Russell F. Warren Chair. These sources did not play a role in the investigation.

Results

Changes in Contact Pressure and Area Across the Entire Sensor

The peak tibial contact pressure in the intact knees was 6 ± 0.5 MPa and 7.4 ± 0.6 MPa at 14% and 45% of the gait cycle, respectively. Across the entire medial tibial plateau, the peak contact pressure after the partial meniscectomy was significantly higher than the values under all other test conditions ($p < 0.015$) at 14% of the gait cycle, but not at 45% of the gait cycle. No significant difference in peak contact pressure was found among the intact meniscus, radial tears involving up to 90% of the rim width, and the inside-out meniscal repair conditions ($p \geq 0.095$) (Fig. 4-A).

A significant reduction in the contact area across the entire sensor was noted between the partial meniscectomy and all other test conditions ($p \leq 0.0004$) at both loading peaks. No significant difference was noted among the intact meniscus, radial tears involving up to 90% of the rim width, or inside-out meniscal repair conditions ($p \geq 0.17$) (Fig. 4-B). Across the entire medial plateau, the mean contact pressure after the partial meniscectomy was significantly higher than the values under all other test conditions at both loading peaks ($p \leq 0.0087$) (Table I).

TABLE II (*continued*)

Contact Area (*mm²*)			
Posteroperipheral		Posterocentral	
14% of Gait Cycle	45% of Gait Cycle	14% of Gait Cycle	45% of Gait Cycle
133.56 ± 4.60	128.19 ± 6.40	180.94 ± 14.67	128.44 ± 16.00
136.75 ± 2.21	129.88 ± 4.94	182.62 ± 13.02	133.19 ± 13.27
136.31 ± 2.04	131.56 ± 3.87	184.31 ± 12.93	140.06 ± 14.90
120.44 ± 8.13	102.00 ± 14.72	176.44 ± 11.06	123.94 ± 15.76
119.88 ± 10.41	103.69 ± 15.61	176.25 ± 10.51	126.31 ± 19.12
67.31 ± 15.94†	54.81 ± 17.52†	126.81 ± 5.48†	109.50 ± 20.45†

Quadrant-Specific Changes in the Location and Distribution of Contact Pressure

Visual representation of the averaged pressure profile across the eight knees illustrated the effect of the phase of gait on the change of pressure distribution as a function of meniscal manipulation (Fig. 5). At 14% of the gait cycle, for example, the posterior portion of the plateau had higher peak contact pressures than the anterior portion under all meniscal conditions. At 45% of the gait cycle, however, the central aspect of the plateau demonstrated higher pressures than the peripheral quadrants under all conditions except partial meniscectomy.

Quadrant analysis at 14% and 45% of the gait cycle confirmed these findings (Figs. 6-A and 6-B). At 14% of the gait cycle, a 90% tear was associated with a significant increase of 1.3 ± 0.5 MPa in peak contact pressure in the posterocentral quadrant as compared with the values associated with the intact condition. Partial meniscectomy led to a further increase in contact pressure in that quadrant of 1.4 ± 0.7 MPa. No significant differences in peak pressure magnitude in any quadrant were found among the intact, 30% radial tear, and 60% radial tear conditions at 14% of the gait cycle ($p \geq 0.29$). No significant differences in peak pressure magnitude in any quadrant were found among the six meniscal conditions at 45% of the gait cycle ($p \geq 0.1$). Partial meniscectomy was associated with a significant reduction in the mean contact area in each quadrant, as compared with the values under all other test conditions ($p < 0.05$), at both peaks. The total contact area was highest in the posterocentral quadrant under all meniscal conditions at 14% of the gait cycle ($p \leq 0.0002$) (Table II).

At 14% of the gait cycle, in both posterior quadrants, the mean contact pressure after partial meniscectomy was significantly higher than the values under all other test conditions ($p \leq 0.01$). At 45% of the gait cycle, there were no significant differences in the mean contact pressure in any quadrant under any test condition ($p > 0.05$) (Table III).

Discussion

The purpose of this study was to measure the contact pressures transmitted to the medial tibial plateau under dynamic physiological loads as a function of the percentage of the meniscal rim involved by a radial tear and repair. Our hypotheses were that (1) there is a threshold size of radial tears above which contact mechanics are adversely affected, and (2) partial meniscectomy results in increased mean and peak contact pressures compared with those found after meniscal repair. Using a novel, dynamic, in vitro cadaver model, we demonstrated that large radial tears of the medial meniscus extending to 90% of the rim width do not significantly increase the magnitude of mean or peak contact pressures compared with those in the intact meniscus under gait loads. Furthermore, tears of 30% and 60% of the radial width of the meniscus cause no change in the location of the peak pressure. Tears involving 90% of the width of the meniscus caused a posterocentral shift in the location of the peak contact pressure, leading us to accept our first hypothesis. Inside-out mattress suture repair of a 90% tear did not adversely affect contact mechanics but did not restore the location of the pressure peak to that of the intact knee. Partial meniscectomy led to an increase in both mean and peak contact pressures and a further posterior shift in pressure location relative to the values under the 90% torn and repaired conditions, leading us to accept our second hypothesis. These results suggest that large radial tears of the medial meniscus are *not equivalent* to functional meniscectomies and that, despite an inability to effectively restore hoop stresses, the residual meniscus continues to play a protective role in load transmission across the joint. This finding is important and supports the goal of meniscal preservation and repair of radial tears.

Radial tears of the meniscus are not uncommon in young patients, and an understanding of their effect on contact mechanics is important to help define an appropriate surgical intervention and minimize long-term complications[11,12,25,45-47]. The body-posterior horn junction of the medial meniscus is a common location for radial tears, accounting for an estimated 28% of all meniscal tears, particularly in the setting of anterior cruciate ligament deficiency[11,14]. The paucity of evidence-based guidelines for the management of radial tears of the medial meniscus[16,17] is due in part to the absence of a robust model in which dynamic pressures on the articular surfaces of the joint can be measured as a function of meniscal manipulation. Theoretically, radial tears extending to the periphery result in

TABLE III Mean Contact Pressure in Each of the Four Quadrants for Each Test Condition at 14% and 45% of the Gait Cycle*

	Contact Pressure (MPa)			
	Anteroperipheral		Anterocentral	
Test Condition	14% of Gait Cycle	45% of Gait Cycle	14% of Gait Cycle	45% of Gait Cycle
Intact	1.08 ± 0.12	0.77 ± 0.15	0.95 ± 0.22	1.81 ± 0.41
30% radial tear	1.00 ± 0.13	0.74 ± 0.15	0.91 ± 0.22	1.70 ± 0.43
60% radial tear	0.94 ± 0.14	0.68 ± 0.16	0.87 ± 0.23	1.63 ± 0.42
90% radial tear	0.66 ± 0.18	0.64 ± 0.20	0.82 ± 0.29	1.75 ± 0.46
Inside-out horizontal mattress repair	0.66 ± 0.18	0.63 ± 0.21	0.82 ± 0.29	1.65 ± 0.45
Partial meniscectomy	0.92 ± 0.51	1.43 ± 0.53	1.09 ± 0.43	2.05 ± 0.47

*The values are given as the mean and standard deviation. †At 14% of the gait cycle, the mean contact pressures in both of the posterior quadrants were significantly higher after partial meniscectomy than under any other test condition ($p < 0.05$). In contrast, there were no significant differences in the mean contact pressure in any quadrant under any test condition at 45% of the gait cycle ($p > 0.05$).

loss of hoop tension and have been described as functionally equivalent to a total meniscectomy[15]. For this reason, partial meniscectomy has historically been the mainstay of surgical treatment for normal meniscal tears. Despite the benefits of short-term pain relief, partial meniscectomy has been associated with a substantially increased incidence of progressive degenerative changes[18-27]. This finding has emphasized the importance of meniscal preservation whenever feasible. More recently, studies have demonstrated that radial meniscal tears can heal if the meniscal rim is adequately prepared, if the tear edges are tightly sutured together, and if the healing site is augmented with biologically active moieties[16,17]. However, it is unclear if such methods can restore the contact mechanics of the injured meniscus to those of its intact state.

Knee joint loads during daily activities such as walking and stair-climbing are multidirectional and dynamic in nature. During gait, loading includes anterior/posterior and axial forces along with internal/external torques and flexion/extension moments. The contact pressures transmitted across the knee joint are sensitive to the direction and magnitude of loading[34,35], suggesting that a dynamic test into which physiological joint loads can be programmed is needed to accurately measure joint contact pressures as a function of meniscal manipulation. The model used for this study was based on technology developed to evaluate the wear performance of total knee replacements—i.e., the Stanmore KC Knee Joint Simulator[36]. Unlike static or quasi-static models that provide data at discrete points in the gait cycle, the simulator allows knees to be dynamically and continuously loaded under conditions that simulate gait[28,31,34,48]. It is a force-controlled apparatus than can be programmed to simultaneously and dynamically control the axial force, anterior force, posterior force, and rotational moment (internal/external torque) as a function of the applied flexion/extension angle profile. Previously used to explore the pressure distribution across ovine knees[43], and demonstrated to reproduce physiological knee kinematics during gait[39], the apparatus was further modified for the purposes of this study to accept and load human cadaver knees. Modifications included the development of a method to reproducibly align the epicondylar axis of the femur with the axis of rotation of the machine and the development of new fixtures to keep the joint rigidly fixed throughout testing.

The magnitudes of contact pressure and contact areas in the intact and partly meniscectomized knees in our study are within the ranges measured in static models[28,31]. However, to recognize the dynamic nature of the test, contact pressure magnitude and distribution in our study was assessed at two points in the stance phase of gait (at 14% and 45% of the gait cycle, which correspond to 15° of flexion and 8° of flexion, with axial loads of 2280 and 2130 N, respectively). At 14% of the gait cycle, the peak pressures were lower and delivered more peripherally in the intact meniscus. With progressively larger tears and after partial meniscectomy, the peak pressure was delivered more centrally on the plateau. At 45% of the gait cycle, however, the pressure peaks were distributed centrally on the plateau in the intact condition. With progressively larger tears and after partial meniscectomy, these pressure peaks increased in magnitude and moved posteriorly on the medial tibial plateau. The observed differences in the magnitude, location, and position of peak contact pressure as a function of meniscal manipulation between the two stages in the gait cycle emphasize the importance of assessing contact pressures over a range of load magnitudes and directions.

Meniscal radial tears of up to 60% had no effect on the magnitude or location of peak contact pressure across the tibial plateau, while 90% tears led to a slight increase in peak pressure magnitude and a posterior shift in the location of the force transmission. These results are in concordance with those in the study by Jones et al., who performed in vitro measurements of circumferential strains in the medial menisci of cadaver knees[49]. Those authors placed strain gauges in the anterior, middle, and posterior sections of the medial meniscus and applied loads of three times body weight at 0° and 30° of flexion. Interestingly, a reduction in strains was detected an-

TABLE III (*continued*)

Contact Pressure (*MPa*)			
Posteroperipheral		Posterocentral	
14% of Gait Cycle	45% of Gait Cycle	14% of Gait Cycle	45% of Gait Cycle
1.93 ± 0.22	1.48 ± 0.38	1.67 ± 0.17	1.83 ± 0.37
1.84 ± 0.23	1.42 ± 0.44	1.74 ± 0.18	1.83 ± 0.37
1.71 ± 0.24	1.34 ± 0.46	1.78 ± 0.20	1.86 ± 0.37
1.62 ± 0.34	1.37 ± 0.57	2.27 ± 0.28	2.17 ± 0.43
1.53 ± 0.33	1.42 ± 0.60	2.15 ± 0.26	2.22 ± 0.39
2.84 ± 0.47†	2.75 ± 0.65	3.15 ± 0.35†	3.01 ± 0.30

teriorly in the specimens with a 50% radial tear, while only complete radial tears rendered the meniscus nonfunctional. The shift in location of force transmission in our study was not corrected by the inside-out mattress repair of the radial tear and was magnified by the partial meniscectomy. The effect of this shift in location of pressure is unclear, but recent work by Andriacchi and Mündermann[50] and Li et al.[51] suggested that articular injury may be associated with subtle shifts in load from conditioned to unconditioned zones of articular cartilage rather than with large differences in the absolute magnitude of transmitted loads. The shift in contact location that we observed may also result in higher stress within the cartilage as regions of thin cartilage in the posteroperipheral aspect of the tibial plateau[51] are subjected to increased loads.

Our study is not without limitations. While it was performed on the medial meniscus, radial tears of the lateral meniscus are also common. It is possible that the adverse effects of partial meniscectomy on contact mechanics in the medial compartment found in this study may be amplified in the less-congruent lateral compartment. Ongoing studies are being completed to define the influence of lateral meniscal lesions on knee contact mechanics. In addition, only physiological loads during gait were evaluated in our study. It is possible that stair-climbing, deep flexion, or pivoting of the knee with other daily activities may apply loads that result in different contact-pressure profiles on the medial plateau under each of the tested meniscal conditions. Finally, this study represents the immediate post-injury, post-treatment characteristics of the meniscus and does not simulate the biological reparative response of the tissue with time.

The clinical application of the findings in this study must be approached with some caution. Our results suggest that partial meniscectomy for the treatment of radial tears of the medial meniscus can have a detrimental effect on the contact mechanics of the knee and that mattress suture repair or even benign neglect of the lesion may be biomechanically favorable alternatives. Given that surgical decision-making is influenced by multiple factors, including symptoms, age, activity level, patient expectations, and concomitant injuries, painful symptomatic tears in patients who seek surgical intervention may necessitate surgical intervention. However, our results emphasize the importance of meniscal preservation and remind surgeons to be cognizant of the adverse contact mechanics associated with partial meniscectomy. Our data suggest that, whenever possible, minimal resection with meniscal preservation should be used in the setting of asymptomatic radial tears incidentally identified on arthroscopy. ■

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References

1. Renström P, Johnson RJ. Anatomy and biomechanics of the menisci. Clin Sports Med. 1990;9:523-38.

2. Krause WR, Pope MH, Johnson RJ, Wilder DG. Mechanical changes in the knee after meniscectomy. J Bone Joint Surg Am. 1976;58:599-604.

3. Voloshin AS, Wosk J. Shock absorption of meniscectomized and painful knees: a comparative in vivo study. J Biomed Eng. 1983;5:157-61.

4. Allen CR, Wong EK, Livesay GA, Sakane M, Fu FH, Woo SL. Importance of the medial meniscus in the anterior cruciate ligament-deficient knee. J Orthop Res. 2000;18:109-15.

5. Allen PR, Denham RA, Swan AV. Late degenerative changes after meniscectomy. Factors affecting the knee after operation. J Bone Joint Surg Br. 1984;66:666-71.

6. Markolf KL, Mensch JS, Amstutz HC. Stiffness and laxity of the knee—the contributions of the supporting structures. A quantitative in vitro study. J Bone Joint Surg Am. 1976;58:583-94.

7. Rodkey WG. Basic biology of the meniscus and response to injury. Instr Course Lect. 2000;49:189-93.

8. McDermott ID, Amis AA. The consequences of meniscectomy. J Bone Joint Surg Br. 2006;88:1549-56.

9. Meakin JR, Shrive NG, Frank CB, Hart DA. Finite element analysis of the meniscus: the influence of geometry and material properties on its behaviour. Knee. 2003;10:33-41.

10. Seedhom BB, Dowson D, Wright V. Proceedings: functions of the menisci. A preliminary study. Ann Rheum Dis. 1974;33:111.

11. Bin SI, Kim JM, Shin SJ. Radial tears of the posterior horn of the medial meniscus. Arthroscopy. 2004;20:373-8.

12. Harper KW, Helms CA, Lambert HS 3rd, Higgins LD. Radial meniscal tears: significance, incidence, and MR appearance. AJR Am J Roentgenol. 2005;185: 1429-34.

13. Kidron A, Thein R. Radial tears associated with cleavage tears of the medial meniscus in athletes. Arthroscopy. 2002;18:254-6.

14. Smith JP 3rd, Barrett GR. Medial and lateral meniscal tear patterns in anterior cruciate ligament-deficient knees. A prospective analysis of 575 tears. Am J Sports Med. 2001;29:415-9.

15. Messner K, Gao J. The menisci of the knee joint. Anatomical and functional characteristics, and a rationale for clinical treatment. J Anat. 1998;193: 161-78.

16. Haklar U, Kocaoglu B, Nalbantoglu U, Tuzuner T, Guven O. Arthroscopic repair of radial lateral meniscus [corrected] tear by double horizontal sutures with inside-outside technique. Knee. 2008;15:355-9.

17. van Trommel MF, Simonian PT, Potter HG, Wickiewicz TL. Arthroscopic meniscal repair with fibrin clot of complete radial tears of the lateral meniscus in the avascular zone. Arthroscopy. 1998;14:360-5.

18. Bolano LE, Grana WA. Isolated arthroscopic partial meniscectomy. Functional radiographic evaluation at five years. Am J Sports Med. 1993;21:432-7.

19. Chatain F, Robinson AH, Adeleine P, Chambat P, Neyret P. The natural history of the knee following arthroscopic medial meniscectomy. Knee Surg Sports Traumatol Arthrosc. 2001;9:15-8.

20. Covall DJ, Wasilewski SA. Roentgenographic changes after arthroscopic meniscectomy: five-year follow-up in patients more than 45 years old. Arthroscopy. 1992;8:242-6.

21. Faunø P, Nielsen AB. Arthroscopic partial meniscectomy: a long-term follow-up. Arthroscopy. 1992;8:345-9.

22. Hoser C, Fink C, Brown C, Reichkendler M, Hackl W, Bartlett J. Long-term results of arthroscopic partial lateral meniscectomy in knees without associated damage. J Bone Joint Surg Br. 2001;83:513-6.

23. Scheller G, Sobau C, Bülow JU. Arthroscopic partial lateral meniscectomy in an otherwise normal knee: clinical, functional, and radiographic results of a long-term follow-up study. Arthroscopy. 2001;17:946-52.

24. Cicuttini FM, Forbes A, Yuanyuan W, Rush G, Stuckey SL. Rate of knee cartilage loss after partial meniscectomy. J Rheumatol. 2002;29:1954-6.

25. Hede A, Larsen E, Sandberg H. The long term outcome of open total and partial meniscectomy related to the quantity and site of the meniscus removed. Int Orthop. 1992;16:122-5.

26. Little C, Smith S, Ghosh P, Bellenger C. Histomorphological and immunohistochemical evaluation of joint changes in a model of osteoarthritis induced by lateral meniscectomy in sheep. J Rheumatol. 1997;24:2199-209.

27. Baratz ME, Fu FH, Mengato R. Meniscal tears: the effect of meniscectomy and of repair on intraarticular contact areas and stress in the human knee. A preliminary report. Am J Sports Med. 1986;14:270-5.

28. Lee SJ, Aadalen KJ, Malaviya P, Lorenz EP, Hayden JK, Farr J, Kang RW, Cole BJ. Tibiofemoral contact mechanics after serial medial meniscectomies in the human cadaveric knee. Am J Sports Med. 2006;34:1334-44.

29. Becker R, Wirz D, Wolf C, Göpfert B, Nebelung W, Friederich N. Measurement of meniscofemoral contact pressure after repair of bucket-handle tears with biodegradable implants. Arch Orthop Trauma Surg. 2005;125:254-60.

30. Agneskirchner JD, Hurschler C, Wrann CD, Lobenhoffer P. The effects of valgus medial opening wedge high tibial osteotomy on articular cartilage pressure of the knee: a biomechanical study. Arthroscopy. 2007;23:852-61.

31. Allaire R, Muriuki M, Gilbertson L, Harner CD. Biomechanical consequences of a tear of the posterior root of the medial meniscus. Similar to total meniscectomy. J Bone Joint Surg Am. 2008;90:1922-31.

32. Dienst M, Greis PE, Ellis BJ, Bachus KN, Burks RT. Effect of lateral meniscal allograft sizing on contact mechanics of the lateral tibial plateau: an experimental study in human cadaveric knee joints. Am J Sports Med. 2007;35: 34-42.

33. Verma NN, Kolb E, Cole BJ, Berkson MB, Garretson R, Farr J, Fregly B. The effects of medial meniscal transplantation techniques on intra-articular contact pressures. J Knee Surg. 2008;21:20-6.

34. Peña E, Calvo B, Martínez MA, Palanca D, Doblaré M. Finite element analysis of the effect of meniscal tears and meniscectomies on human knee biomechanics. Clin Biomech (Bristol, Avon). 2005;20:498-507.

35. Huang A, Hull ML, Howell SM. The level of compressive load affects conclusions from statistical analyses to determine whether a lateral meniscal autograft restores tibial contact pressure to normal: a study in human cadaveric knees. J Orthop Res. 2003;21:459-64.

36. Walker PS, Blunn GW, Perry JP, Bell CJ, Sathasivam S, Andriacchi TP, Paul JP, Haider H, Campbell PA. Methodology for long-term wear testing of total knee replacements. Clin Orthop Relat Res. 2000;372:290-301.

37. Walker PS, Blunn GW, Broome DR, Perry J, Watkins A, Sathasivam S, Dewar ME, Paul JP. A knee simulating machine for performance evaluation of total knee replacements. J Biomech. 1997;30:83-9.

38. DesJardins JD, Banks SA, Benson LC, Pace T, LaBerge M. A direct comparison of patient and force-controlled simulator total knee replacement kinematics. J Biomech. 2007;40:3458-66.

39. van Houtem M, Clough R, Khan A, Harrison M, Blunn GW. Validation of the soft tissue restraints in a force-controlled knee simulator. Proc Inst Mech Eng H. 2006;220:449-56.

40. Martens TA, Hull ML, Howell SM. An in vitro osteotomy method to expose the medial compartment of the human knee. J Biomech Eng. 1997;119: 379-85.

41. Drewniak EI, Crisco JJ, Spenciner DB, Fleming BC. Accuracy of circular contact area measurements with thin-film pressure sensors. J Biomech. 2007;40:2569-72.

42. Bachus KN, DeMarco AL, Judd KT, Horwitz DS, Brodke DS. Measuring contact area, force, and pressure for bioengineering applications: using Fuji Film and TekScan systems. Med Eng Phys. 2006;28:483-8.

43. Cottrell JM, Scholten P, Wanich T, Warren RF, Wright TM, Maher SA. A new technique to measure the dynamic contact pressures on the tibial plateau. J Biomech. 2008;41:2324-9.

44. Taylor SJ, Perry JS, Meswania JM, Donaldson N, Walker PS, Cannon SR. Telemetry of forces from proximal femoral replacements and relevance to fixation. J Biomech. 1997;30:225-34.

45. Baker BE, Peckham AC, Pupparo F, Sanborn JC. Review of meniscal injury and associated sports. Am J Sports Med. 1985;13:1-4.

46. Nielsen AB, Yde J. Epidemiology of acute knee injuries: a prospective hospital investigation. J Trauma. 1991;31:1644-8.

47. Magee T, Shapiro M, Williams D. MR accuracy and arthroscopic incidence of meniscal radial tears. Skeletal Radiol. 2002;31:686-9.

48. von Lewinski G, Stukenborg-Colsman C, Ostermeier S, Hurschler C. Experimental measurement of tibiofemoral contact area in a meniscectomized ovine model using a resistive pressure measuring sensor. Ann Biomed Eng. 2006;34:1607-14.

49. Jones RS, Keene GC, Learmonth DJ, Bickerstaff D, Nawana NS, Costi JJ, Pearcy MJ. Direct measurement of hoop strains in the intact and torn human medial meniscus. Clin Biomech (Bristol, Avon). 1996;11:295-300.

50. Andriacchi TP, Mündermann A. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. Curr Opin Rheumatol. 2006;18: 514-8.

51. Li G, Park SE, DeFrate LE, Schutzer ME, Ji L, Gill TJ, Rubash HE. The cartilage thickness distribution in the tibiofemoral joint and its correlation with cartilage-to-cartilage contact. Clin Biomech (Bristol, Avon). 2005;20:736-44.