

Nonanatomic Location of the Posterior Horn of a Medial Meniscal Autograft Implanted in a Cadaveric Knee Adversely Affects the Pressure Distribution on the Tibial Plateau

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ABSTRACT

Nonanatomic placement of the posterior horn may occur during arthroscopic implantation of a meniscal transplant. The objective of this study was to determine whether nonanatomic placement adversely affects the contact pressure distribution on the medial tibial plateau. Medial meniscal autografts were placed in eight cadaveric knees with the posterior horn tunnel in nonanatomic locations (5 mm medial and 5 mm posterior) and in the anatomic location. The contact pressure distribution of the medial articular surface of the tibia was measured with pressure-sensitive film under a 1200-N compressive load at 0°, 15°, 30°, and 45° of flexion. The maximum pressure, mean pressure, contact area, and anterior/posterior and medial/lateral locations of the centroid of contact area were compared. Placement of the posterior horn tunnel in the nonanatomic medial location caused a significant increase in the normalized maximum pressure over all flexion angles, an increase in the normalized mean pressure at 45°, and a posterior shift in the centroid of contact area over all flexion angles. Placement in the nonanatomic posterior location caused a significant posterior shift in the centroid of contact area over all flexion angles. Surgeons should place the posterior horn tunnel of a medial meniscal transplant within a tolerance tighter

than 5 mm medial and 5 mm posterior to the anatomic location because nonanatomic placement significantly alters the contact pressure distribution.

The goal of medial meniscal transplantation is to prevent degenerative changes that can result from meniscectomy.^{14,16} A reasonable assumption is that degenerative arthritis is more likely to be prevented when the medial meniscal transplant restores the contact pressure distribution of the articular surface of the tibia to normal. Variables describing the contact pressure distribution (maximum pressure, mean pressure, contact area, and the anterior/posterior and medial/lateral locations of the centroid of contact area) are referred to as contact variables. They are restored closest to normal at implantation when the two bone plugs, which are attached to the anterior and posterior horns of the meniscal transplant, are fixed in anatomically placed tunnels.³

The posterior horn tunnel of a medial meniscal allograft may not be placed anatomically during arthroscopic implantation because the tibial eminence obscures the surgeon's view of the insertion of the posterior horn. It is unknown whether nonanatomic placement of the posterior horn tunnel of a medial meniscal transplant affects the contact variables of the tibial plateau. The objective of this study was to determine whether the contact variables with the posterior horn tunnel placed nonanatomically, either 5 mm medial or 5 mm posterior to the anatomic location, are different from those with the posterior horn tunnel placed in the proper anatomic location.

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No author or related institution has received any financial benefit from research in this study. See "Acknowledgment" for funding information.

MATERIALS AND METHODS

Selection of Specimens

Anteroposterior and lateral roentgenograms, MRI scans, and direct visual inspection were used to screen human cadaveric knee specimens for inclusion in the study. Knee specimens without joint space narrowing, osteophytes, chondrocalcinosis, meniscal tears, prior knee operations, and gross degenerative changes were included. Eight knee specimens obtained from separate donors with an average age of 56 years (age range, 38 to 70) met the inclusion criteria.

Preparation and Alignment of the Knee in the Load-Application System

Each knee was prepared and mechanically aligned in the load-application system.⁴ Soft tissues within 10 cm of the joint line were left intact, and the rest were removed. Steel rods, 12.5 mm in diameter, were secured in the medullary canals of the femur and tibia with polymethyl methacrylate cement to interface the knee with the load-application system. The tibia and femur were inserted in rectangular tubes bolted to the load-application system. The knee was aligned with use of the functional axes approach, a technique with good repeatability.⁵ The femur, tibia, and steel rods were cemented in the rectangular tubes to preserve the alignment. The rectangular tubes were unbolted from the load-application system and the knee was removed.

Osteotomy and Harvest of the Meniscal Autograft

An osteotomy was performed to expose the medial hemi-joint using a previously described technique.¹² The osteotomy did not alter the contact variables of the medial articular surface of the tibia after the medial femoral condyle was reassembled with bolts.

The medial meniscus was harvested as an autograft by leaving a bone plug attached to the anatomic center of the posterior and anterior horns. The center of the posterior horn was identified using landmarks. The medial edge of the posterior horn was determined by inserting a thin strip of metal between the meniscus and the tibial articular surface and sliding the strip laterally until it was flush against the medial edge of the attachment of the posterior horn (Fig. 1). The anterior, posterior, and lateral edges of the posterior horn were visualized and traced with a pen. The anatomic center of the posterior horn was defined as the center of these four boundaries. A 2.4-mm diameter K-wire was drilled through the anatomic center, exiting distally on the anterolateral aspect of the tibia. The same technique was used to identify the anatomic center of the anterior horn. Another 2.4-mm diameter K-wire was drilled through the anatomic center of the anterior horn of the meniscus, exiting distally on the posteromedial aspect of the tibia. The periphery of the body of the meniscus was sharply detached, leaving a 1 to 2 mm wide rim attached to the capsule. A 10-mm cannulated reamer was drilled from distal to proximal over each

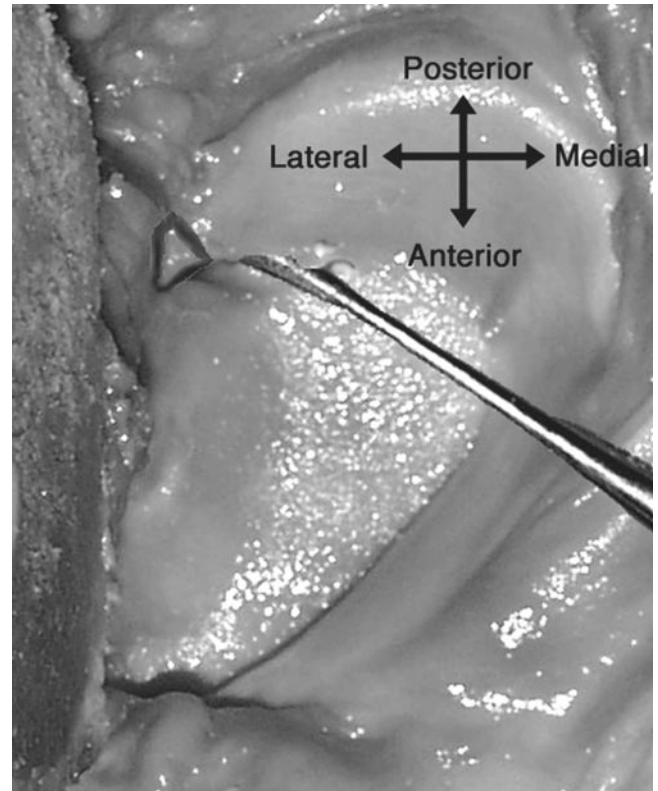


Figure 1. Superior view of the articular surface of the tibia and medial meniscus illustrating the technique used to define the center of the posterior horn. The lines outline the medial, anterior, posterior, and lateral edges of the posterior horn. The center of the posterior horn was defined as the center of these four boundaries.

guidewire through the cortex to a depth of 10 mm. A cannulated coring reamer, with a 9-mm outside diameter and an 8-mm inside diameter (9-mm Coring Reamer, AR1223S, Arthrex, Naples, Florida), was advanced over each of the guidewires through the articular surface without damaging the insertion of the meniscal horns on the bone plugs. The bone plugs were shortened to a length of 15 mm and reinforced with polymethyl methacrylate to prevent failure of the bone plugs, which can occur during compression of the joint.³

Technique for Positioning the Bushing for Anatomic and Nonanatomic Tunnel Locations

The technique for placing the posterior horn tunnel in the three different locations required drilling an oversized tunnel consisting of two 10-mm diameter tunnels contiguous with the anatomic tunnel (Fig. 2). The osteotomy was disassembled, and an offset drill guide was inserted into the anatomic tunnel to drill the second tunnel. For a right knee, the drill guide was rotated to the medial side of the tibia, and the tunnel for the nonanatomic placement in the medial location was drilled. For a left knee, the drill guide was rotated to the posterior side of the tibia, and the

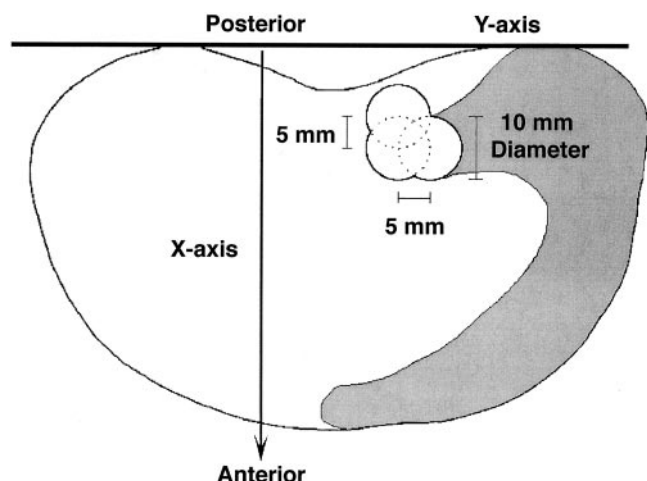


Figure 2. Superior view of the articular surface of the tibia showing the location and dimensions of the anatomic tunnel and medial and posterior nonanatomic tunnels for the posterior horn bone plug of the medial meniscus. The posterior wall of the posterior tunnel is in close proximity to the posterior edge of the tibial articular surface.

tunnel for nonanatomic placement in the posterior location was drilled. The drill guide was removed and a second drill guide was inserted to position the remaining tunnel. For a right knee, the tunnel for the nonanatomic placement in the posterior location was drilled. For a left knee, the tunnel for the nonanatomic placement in the medial location was drilled. The walls of the tunnels were reinforced with cement.

A series of three aluminum bushings was used to position the bone plug in the three tunnel locations. Each bushing was constructed so that it left one of the three tunnels clear while filling the remainder of the cross section created by the three tunnels (Fig. 2). Each bushing was selected at random and inserted flush with the tibial plateau. To prevent the bushing from migrating distally, an aluminum plug was inserted up the tunnel and pinned to the tibia with a K-wire. The bone plug attached to the posterior horn was cemented in the bushing. The anterior horn was cemented in the anterior tunnel. The contact pressure distribution was measured using a technique described later. The bone plug/bushing unit was removed from the posterior tunnel, and the process was repeated in each of the other two locations using the appropriate bushing selected at random. The measurement of the contact pressure distribution was repeated.

Pressure-Sensitive Film Packets

Two ranges of pressure-sensitive film were used (Super-low-range and low-range pressure film, Fuji Prescale Film; Fuji Corp., Tokyo, Japan).¹⁴ Super-low-range pressure film, which measures pressures in the rated range of 0.5 to 2.5 MPa, was selected because it provides a more

accurate measurement of the contact area than does low-range pressure film. Low-range pressure film, which measures pressure in the rated range of 2.5 to 10 MPa, was selected because it provides a more accurate measurement of maximum pressure than does super-low-range pressure film at the physiologic compressive loads that were applied to the knee.³

Film packets were created for each knee to match both the size and shape of the medial tibial plateau using a previously described technique.^{3,12} Briefly, a 0.8-mm thick piece of Teflon (polytetrafluoroethylene; E.I. du Pont de Nemours and Company, Wilmington, Delaware) was trimmed to fit on the articular surface under the medial meniscus. This template was used to prepare 0.25-mm thick polyethylene film packets for each range of film. All film packets for a specimen were sealed at the same time to standardize the humidity, and the relative humidity in the room was recorded to calibrate the film.¹¹

Loading the Knee Specimens

The specimen, with the posterior horn tunnel in one of the three locations, was once again placed in the load-application system and preconditioned by applying a compressive load building up to 1200 N over 15 seconds, maintaining this load for 5 seconds, and removing the load. This loading cycle was applied three times with the knee at 0° and 45° of flexion.

After preconditioning, the pressure-sensitive film was inserted beneath the meniscus, after which the specimens were loaded in compression. Three factors that had the potential to affect the exposure of the pressure-sensitive film were controlled during the application of the compressive load: shear, overshoot, and loading time.¹² Three film packets of each film range (six per flexion angle) were exposed at 0°, 15°, 30°, and 45° of flexion selected at random at a compressive load of 1200 N. The time of the load application was the same as that for the preconditioning load cycle. This range of flexion angles was chosen because it reproduces the position of the knee during the stance phase of gait.¹⁵ The 1200-N load is approximately 1.5 times body weight, which approaches the physiologic compression of the knee during walking.¹⁰ The position of each film packet on the tibial plateau was recorded by inserting two pins through two 1.6-mm diameter tunnels drilled through the tibia and the articular surface. The two pins created dots in peripheral areas of the film that were minimally exposed during loading.⁹

After all of the pressure tests were concluded, the knee was disarticulated, and the positions of the pins on the articular surface of the tibial plateau were photographed with a digital camera.⁸ The relationship of the two pins to the posterior osteochondral junction of the medial and lateral compartments was used later to determine the location of the centroid of contact area in an anatomically based coordinate system.

Data Analysis

The film packets exposed at all four flexion angles for a specific joint condition were scanned simultaneously with a high-resolution scanner (Model ScanJet 4C, Hewlett-Packard Corp., Tracy, California).¹² The intensity of the film stain was converted to pressure using a calibration curve determined at the same relative humidity under which the film was sealed.⁷ The maximum pressure, mean pressure, contact area, and location of the centroid of contact area were determined from each scanned image by using image analysis software (NIH Image, version 3b for Windows NT, Scion Corporation, Frederick, Maryland) and a personal computer.

The maximum pressure at a flexion angle was determined by averaging the maximum pressure from the three trials using only the low-range film (Table 1). The maximum pressure was normalized (Table 2) by computing the difference in maximum pressure between the nonanatomic location and the anatomic location and dividing by the difference in maximum pressure between the meniscectomized knee and the anatomic location.

The contact area at each flexion angle was determined by averaging the contact area from the three trials using only the super-low-range film (Table 3). The contact area was normalized (Table 4) by computing the difference in contact area between the nonanatomic location and the anatomic location and dividing by the difference in contact area between the meniscectomized knee and the anatomic location.

The mean pressure at each flexion angle was determined in two steps. In the first step, the mean pressure for a trial was calculated by combining the pressure measurements made with both the super-low-range film and the low-range film (Appendix A). In the second step, the

mean pressure at a flexion angle was determined by averaging the mean pressure from the three trials (Table 5). The mean pressure at a flexion angle was normalized (Table 6) by computing the difference in mean pressure between the nonanatomic location and the anatomic location and dividing by the difference in mean pressure between the meniscectomized knee and the anatomic location.

The centroid of contact area at a flexion angle was determined in an anatomic coordinate system (Appendix B). The origin of the anatomic coordinate system on the articular surface of the tibia was the center of the anatomic tunnel, the Y-axis was a line drawn connecting the posterior osteochondral junctions of the medial and lateral compartments (+ medial, - lateral), and the X-axis was a line drawn perpendicular to the Y-axis (+ anterior, - posterior).

The maximum pressure, mean pressure, contact area, and the X and Y locations of the centroid of contact area were compared between the medial and the anatomic locations and between the posterior and the anatomic locations of the posterior horn tunnel using paired *t*-tests. In the first analysis, the data were pooled over all flexion angles. If any of these analyses did not reveal a significant difference, then more detailed analyses were performed at each flexion angle for that contact variable. A difference was considered significant when *P* < 0.05.

RESULTS

Placement of the posterior horn tunnel at the medial nonanatomic location caused significant changes in three of the contact variables. The normalized maximum pressure was significantly increased when the

TABLE 1
Maximum Contact Pressures (MPa) on the Medial Tibial Plateau with the Posterior Horn Tunnel for the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion angle				Pooled
	0°	15°	30°	45°	
Anatomic	3.1 ± 1.1	3.8 ± 1.0	3.7 ± 1.0	4.0 ± 1.2	3.7 ± 1.1
Medial	3.6 ± 1.5	3.6 ± 1.0	4.5 ± 1.6	5.0 ± 2.0	4.2 ± 1.6
Posterior	2.7 ± 1.1	3.0 ± 0.8	3.8 ± 1.1	4.4 ± 1.3	3.5 ± 1.2
Meniscectomy	3.3 ± 1.2	4.5 ± 1.8	6.3 ± 1.6	7.0 ± 0.7	5.2 ± 2.0

^a Data are means ± SD for eight cadaveric knees.

TABLE 2
Normalized Maximum Contact Pressure on the Medial Tibial Plateau with the Posterior Horn Tunnel for the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion angle				Pooled
	0°	15°	30°	45°	
Anatomic	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Medial	3.1 ± 4.3 (<i>P</i> = 0.079)	0.0 ± 1.7 (<i>P</i> = 0.999)	0.5 ± 0.5 (<i>P</i> = 0.026)	0.4 ± 0.4 (<i>P</i> = 0.041)	1.0 ± 2.6 (<i>P</i> = 0.035)
Posterior	-0.1 ± 1.3 (<i>P</i> = 0.801)	1.6 ± 3.0 (<i>P</i> = 0.199)	0.3 ± 0.4 (<i>P</i> = 0.111)	0.1 ± 0.2 (<i>P</i> = 0.074)	0.5 ± 1.7 (<i>P</i> = 0.141)
Meniscectomy	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0

^a Data are means ± SD for eight cadaveric knees. *P* values indicate difference compared with anatomic tunnel position. Medial placement caused the normalized maximum pressure to increase significantly above that of the anatomic location for the pooled data.

TABLE 3

Contact Area (in Square Millimeters) on the Medial Tibial Plateau with the Posterior Horn Tunnel of the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion angle				Pooled
	0°	15°	30°	45°	
Anatomic	156.9 ± 88.6	188.9 ± 105.4	171.4 ± 54.1	192.8 ± 86.9	177.5 ± 82.8
Medial	168.0 ± 77.6	190.7 ± 120.5	219.4 ± 116.0	208.0 ± 141.7	196.5 ± 112.2
Posterior	193.4 ± 86.5	218.4 ± 106.4	223.6 ± 80.4	224.2 ± 99.9	214.9 ± 89.4
Meniscectomy	183.9 ± 85.0	189.9 ± 67.4	158.5 ± 50.1	146.7 ± 67.0	169.8 ± 67.5

^a Data are means ± SD for eight cadaveric knees.

TABLE 4

Normalized Contact Area on the Medial Tibial Plateau with the Posterior Horn Tunnel of the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion Angle				Pooled
	0°	15°	30°	45°	
Anatomic	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Medial	-1.0 ± 2.3 (<i>P</i> = 0.252)	0.2 ± 1.3 (<i>P</i> = 0.738)	-0.5 ± 4.2 (<i>P</i> = 0.754)	1.3 ± 2.4 (<i>P</i> = 0.154)	0.0 ± 2.7 (<i>P</i> = 0.994)
Posterior	0.7 ± 1.3 (<i>P</i> = 0.220)	1.3 ± 2.2 (<i>P</i> = 0.183)	0.0 ± 2.0 (<i>P</i> = 0.983)	0.8 ± 2.1 (<i>P</i> = 0.333)	0.7 ± 1.9 (<i>P</i> = 0.067)
Meniscectomy	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0

^a Data are means ± SD for eight cadaveric knees. *P* values indicate difference compared with anatomic tunnel position. There were no significant differences.

TABLE 5

Mean Contact Pressure (in Megapascals) on the Medial Tibial Plateau with the Posterior Horn Tunnel of the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion angle				Pooled
	0°	15°	30°	45°	
Anatomic	1.0 ± 0.3	1.1 ± 0.5	1.2 ± 0.5	1.2 ± 0.4	1.2 ± 0.4
Medial	1.1 ± 0.3	1.2 ± 0.5	1.3 ± 0.5	1.5 ± 0.6	1.3 ± 0.5
Posterior	0.8 ± 0.2	0.8 ± 0.2	1.2 ± 0.4	1.4 ± 0.4	1.1 ± 0.4
Meniscectomy	1.1 ± 0.4	1.4 ± 0.6	1.7 ± 0.6	2.3 ± 0.6	1.6 ± 0.7

^a Data are means ± SD for eight cadaveric knees.

TABLE 6

Normalized Mean Contact Pressure on the Medial Tibial Plateau with the Posterior Horn Tunnel of the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion angle				Pooled
	0°	15°	30°	45°	
Anatomic	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Medial	4.8 ± 10.4 (<i>P</i> = 0.267)	0.4 ± 0.6 (<i>P</i> = 0.155)	-4.2 ± 10.3 (<i>P</i> = 0.327)	0.4 ± 0.4 (<i>P</i> = 0.048)	0.3 ± 7.7 (<i>P</i> = 0.805)
Posterior	3.1 ± 5.1 (<i>P</i> = 0.159)	0.4 ± 1.0 (<i>P</i> = 0.381)	-1.1 ± 2.6 (<i>P</i> = 0.304)	0.1 ± 0.3 (<i>P</i> = 0.320)	0.6 ± 3.2 (<i>P</i> = 0.312)
Meniscectomy	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0

^a Data are means ± SD for eight cadaveric knees. *P* values indicate differences compared with the anatomic tunnel position. There were no significant differences.

pooled data were analyzed (range, 0 to 3.1; *P* = 0.035) (Table 2). The centroid of contact area shifted posteriorly from that of the anatomic location when the pooled data were analyzed (range, 3.8 to 5.2 mm; *P* < 0.001) (Table 7). Placement of the posterior horn tunnel at the medial nonanatomic location did not significantly affect the other three contact variables when the pooled data were analyzed (normalized contact area, *P* = 0.994; normalized mean pressure, *P* = 0.805; Y coordinate of

the centroid of contact area, *P* = 0.222) (Table 8). In the more detailed analyses at individual flexion angles, placement of the posterior horn tunnel in the nonanatomic medial location caused an increase only in the normalized mean pressure at 45° of flexion (*P* = 0.048).

Placement of the posterior horn tunnel in the nonanatomic posterior location caused a significant change in only one of the five contact variables. The centroid of contact area was found to be displaced posteriorly from

TABLE 7
Anatomic X-Coordinate of the Centroid of Contact Area (in Millimeters) on the Medial Tibial Plateau with the Posterior Horn Tunnel of the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion angle				Pooled
	0°	15°	30°	45°	
Anatomic	0	0	0	0	0
Medial	-4.8 ± 3.1 (<i>P</i> = 0.004)	-5.1 ± 1.8 (<i>P</i> = 0.000)	-5.2 ± 2.7 (<i>P</i> = 0.001)	-3.8 ± 3.5 (<i>P</i> = 0.017)	-4.3 ± 3.3 (<i>P</i> = 0.000)
Posterior	-4.5 ± 2.1 (<i>P</i> = 0.001)	-2.7 ± 2.1 (<i>P</i> = 0.007)	-2.4 ± 1.5 (<i>P</i> = 0.002)	-1.6 ± 1.4 (<i>P</i> = 0.013)	-2.8 ± 2.0 (<i>P</i> = 0.000)
Meniscectomy	-4.0 ± 2.7 (<i>P</i> = 0.004)	-4.0 ± 3.0 (<i>P</i> = 0.007)	-4.0 ± 2.0 (<i>P</i> = 0.001)	-3.5 ± 1.8 (<i>P</i> = 0.001)	-3.9 ± 2.3 (<i>P</i> = 0.000)

^a Data are means ± SD for eight cadaveric knees. An anterior shift in the coordinate from the centroid of contact area with the posterior tunnel in the anatomic location is positive. Both of the two nonanatomic tunnel locations caused a significant posterior shift of the centroid of contact area from that of the anatomic location over all flexion angles.

TABLE 8
Anatomic Y-Coordinate of the Centroid of Contact Area (in Millimeters) on the Medial Tibial Plateau with the Posterior Horn Tunnel of the Medial Meniscus Located Anatomically, Medially, and Posteriorly and with the Meniscus Removed^a

Condition	Flexion angle				Pooled
	0°	15°	30°	45°	
Anatomic	0	0	0	0	0
Medial	0.1 ± 0.8 (<i>P</i> = 0.851)	0.3 ± 0.8 (<i>P</i> = 0.353)	-0.2 ± 0.8 (<i>P</i> = 0.511)	-0.2 ± 0.6 (<i>P</i> = 0.343)	0.2 ± 0.7 (<i>P</i> = 0.222)
Posterior	0.0 ± 0.6 (<i>P</i> = 0.838)	-0.1 ± 0.7 (<i>P</i> = 0.778)	0.1 ± 0.5 (<i>P</i> = 0.974)	-0.1 ± 0.5 (<i>P</i> = 0.497)	0.0 ± 0.6 (<i>P</i> = 0.708)
Meniscectomy	0.1 ± 0.3 (<i>P</i> = 0.432)	-0.3 ± 1.1 (<i>P</i> = 0.417)	-0.2 ± 0.7 (<i>P</i> = 0.442)	-0.1 ± 0.6 (<i>P</i> = 0.649)	0.1 ± 0.7 (<i>P</i> = 0.336)

^a Data are means ± SD for eight cadaveric knees. A medial shift in the coordinate from the centroid of contact area with the posterior tunnel in the anatomic location is positive. There were no significant differences.

the anatomic location when the pooled data were analyzed (range, 1.6 to 4.5 mm; *P* < 0.001) (Table 7). Placement of the posterior horn tunnel in the nonanatomic location did not significantly affect any of the other contact variables when either the pooled data were analyzed (normalized maximum pressure, *P* = 0.141; normalized contact area, *P* = 0.067; normalized mean pressure, *P* = 0.312; Y-coordinate of centroid of contact area, *P* = 0.708) or data at individual flexion angles were analyzed.

DISCUSSION

The purpose of this study was to determine whether the contact variables with the posterior horn tunnel placed in either a medial or posterior nonanatomic location are different from the contact variables with the posterior horn tunnel placed in the proper anatomic location. The key findings were that 1) placement of the posterior horn tunnel in the nonanatomic medial location increased the normalized maximum pressure and shifted the centroid of contact area posteriorly, and 2) placement of the posterior horn tunnel in the nonanatomic posterior location also shifted the centroid of contact area posteriorly. Before discussing the importance of these findings, several methodologic issues should be reviewed.

Methodologic Issues

The choices of the direction and magnitude of the placement of the nonanatomic tunnels in relation to the ana-

tomically located tunnels were based on a pilot study. A single orthopaedic surgeon used standard medial and lateral arthroscopic portals to drill a guidewire in what was perceived to be the center of the insertion of the posterior horn in five cadaveric knees.¹⁷ The direction and magnitude of deviations of the guidewire from the anatomic center of the posterior horn were determined after disarticulating the knees. The selection of the posterior horn tunnel performed arthroscopically varied up to 6.2 mm medially and up to 5.7 mm posteriorly. Although the maximum deviations used in the pilot study were slightly larger than the 5 mm used in the current study, the value of 5 mm was a practical upper limit for two reasons. First, moving the nonanatomic tunnels farther than 5 mm would have required the removal of more of the tibial articular surface, which might have altered the contact pressure distribution. Second, moving the posterior tunnel by more than 5 mm might have compromised the integrity of the cortical bone of the tibia because of reduced wall thickness (Fig. 2).

By limiting the movement of the nonanatomic tunnels to 5 mm from the anatomic location and by using bushings to change the tunnel location, the measurement of contact variables and, hence, the conclusions of the study were not affected by these procedures. Inasmuch as both the anatomic and nonanatomic posterior horn tunnels were located in regions devoid of pressure stains, it is unlikely that the measurements were affected. Also, the bushings were inserted flush with the

articular surface of the tibia, which prevented them from causing artifacts in the pressure stain during exposure of the film. The values of the contact variables were comparable to those reported in previous studies,^{3,12} thus confirming that the tunnels and the bushing did not affect the results of this study.

Beyond comparing the results for the nonanatomic locations with those of the anatomic location, other comparisons were possible but were not performed. Although results for each of the nonanatomic locations could have been compared with those of the intact meniscus, this was not performed because the experiment design would have been confounded. The results for the nonanatomic locations included not only the effect of posterior horn location but also the effect of the method of surgical fixation. Thus, making comparisons that included both independent variables would not have isolated the location of the posterior horn. Also, although results for the anatomic location could have been compared with those for the intact meniscus to evaluate the effectiveness of the surgical fixation method in restoring normal tibial contact, this was not performed because this comparison has been made previously.³

A discussion of how the use of pressure-sensitive film and elderly specimens could affect the contact variables has been detailed previously.^{3,12} The pressure-sensitive film did not indicate the actual contact area because the pressure must exceed a threshold (0.5 MPa for super-low-range pressure film) to create a stain. Also the "normal" contact pressure distribution of a knee from an elderly specimen is likely to be different from that of a younger specimen. Nevertheless, neither the use of the film nor the use of older specimens (70 years of age) compromised the conclusions of the study because each knee served as its own control in the statistical analysis. Thus, any systematic changes in contact variables because of either the film threshold or the age of the specimen were eliminated.

Several issues were considered in the selection of a compressive load for this study. Ideally, the applied compressive load should have been about 1500 N (2 times body weight) to approximate the load across the knee during walking.¹⁰ Although meniscal allografts from donors younger than 48 years of age can tolerate a compressive load of 1800 N,¹⁴ in our study the reinforced bone plugs would sometimes fail at loads substantially above 1200 N (1.5 times body weight). Even though a load of 1200 N was less than ideal, the conclusions regarding the location of the posterior horn are still meaningful because the same load was applied for all knee conditions and because this load was 80% of the physiologic load. However, it should be noted that increasing the compressive load further might have increased differences in the contact variables between the nonanatomic and anatomic locations, thus increasing the number of comparisons that were detected as being significantly different.

Interpretation of Results

This study conducted in human cadaveric knees showed that placing the posterior horn tunnel of a medial menis-

cal autograft in either of the two nonanatomic locations caused the contact variables to be affected adversely. The nonanatomic medial location caused the normalized maximum pressure to increase, the location of the centroid of contact area to shift posteriorly, and the normalized mean pressure to increase at one flexion angle. The nonanatomic posterior location also caused the location of the centroid of contact area to shift posteriorly.

The cause of the increase in the normalized maximum pressure for the nonanatomic medial location may have been a slackening in the circumferential tension of the meniscus. Placement of the posterior horn bone plug in the medial tunnel caused the meniscal transplant to displace toward the periphery of the joint, with the consequence that the meniscus became slack circumferentially. Inasmuch as the circumferential tensile modulus has been shown to be an important determinant of meniscal load-sharing,⁶ introducing slackness circumferentially caused decreased load-sharing on the part of the meniscus. With the tibial articular surface experiencing greater loads, the normalized maximum pressure increased as a result. Therefore, a surgical technique that leads to a reduction in the circumferential tension of the meniscal transplant would be expected to adversely affect load-sharing. Our findings suggest that placement of the posterior horn tunnel 5 mm medial to the anatomic location should be avoided.

Placement of the posterior horn tunnel in the nonanatomic posterior location had less of an effect on pressure than placing it in the nonanatomic medial location because the posterior placement did not increase either the normalized maximum or the normalized mean pressure. One reason that the pressures were not different is that the circumferential tension increased with the posterior horn placed in the nonanatomic posterior location. This placement increased the load-sharing on the part of the meniscus, which may have offset any increase in the contact pressure that would be expected to accompany the increase in the area of the tibial articular surface not covered by the meniscus. Our findings suggest that placement of the posterior horn tunnel 5 mm posterior to the anatomic location is not as detrimental to the pressure of the articular surface of the tibia as placement of the posterior horn tunnel 5 mm medial to the anatomic location.

Placement of the posterior horn in either of the nonanatomic locations caused significant shifts in the centroid of contact area that were consistently in the posterior direction (Tables 7 and 8). Shifts in the posterior direction occurred because the high-pressure region in the medial compartment tends to be located in its posterior half.¹ Hence, relocating the posterior horn either medially or posteriorly from the anatomic location shifted the region of contact posteriorly.

One possible consequence of a posterior shift in the centroid of contact area, which exceeded 5 mm for some flexion angles (Table 7), is that the articular cartilage may have to remodel to prevent degenerative arthritis. Loaded regions of articular cartilage have a higher proteoglycan content and, hence, a greater aggregate compression modulus than unloaded cartilage.^{2,13} Therefore, a shift in the

location of the centroid of contact area could cause accelerated articular wear if the cartilage does not alter the proteoglycan content in response to the change in compressive load.

Our findings suggest that surgeons should strive to place the posterior horn tunnel within a tolerance tighter than 5 mm to the anatomic location so that the contact pressure distribution can be restored closer to normal at implantation. Placement of the posterior horn tunnel in either a medial or a posterior nonanatomic location adversely affects contact variables at implantation, which may affect the ability of a meniscal transplant to prevent the development of degenerative arthritis. Perfecting surgical techniques so that the posterior horn tunnel can be placed within a tolerance tighter than 5 mm to the anatomic location may improve the long-term performance of a meniscal transplant.

ACKNOWLEDGEMENT

The authors are grateful to the Whitaker Foundation for providing part of the financial support for this project.

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APPENDIX A

The mean pressure for each trial was determined by combining the information from both the super-low-range and low-range pressure-sensitive films (Fig. A1). The pressure in the contact area of the super-low-range film corresponding to the contact area of the low-range film was set to zero, forming a donut-shaped contact area (A_D). The mean pressure (P_D) in the donut-shaped area (A_D) on the super-low-range film and the mean pressure (P_L) in the area (A_L) on the low-range film were computed by averaging the pressure in each pixel of the respective areas. The compressive force (CFD) of the donut-shaped area was determined by multiplying the mean pressure (P_D) in this donut-shaped area by the donut-shaped area (A_D). The compressive force of the low-range film (CFL) was calculated by multiplying the mean pressure (P_L) by the contact area (A_L). The mean pressure for a trial was calculated by adding the two compressive forces (CFD + CFL) and dividing by the contact area of the super-low-range pressure film ($A_D + A_L$).

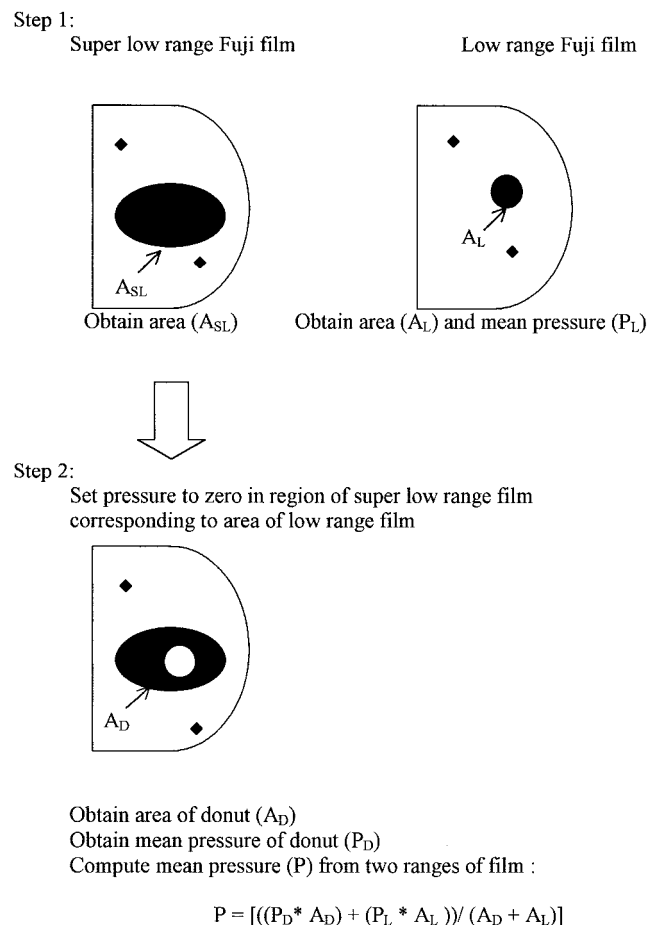


Figure A1. The technique used to calculate the mean pressure from two ranges of pressure-sensitive film.

APPENDIX B

Determining the change in the location of the centroid of contact area required the transformation of the coordinates of the centroid of contact area from the local coordinate system (x, y) on the pressure-sensitive film to an anatomic coordinate system (X, Y) on the articular surface of the tibia (Fig. B1). The origin of the local coordinate system on the pressure-sensitive film was the posterior pin mark, the x -axis was a line connecting the anterior and posterior pin marks, and the y -axis was a line drawn perpendicular to the x -axis at the origin. For each tunnel location, the average local coordinate of the centroid of contact area at a flexion angle was determined by averaging the coordinates of the centroid of contact area from the three trials. The origin of the anatomic coordinate system on the articular surface of the tibia was the center of the anatomic tunnel, the Y -axis was a line drawn connecting the posterior osteochondral junctions of the medial and lateral compartments (+ medial, - lateral), and the X -axis was a line drawn perpendicular to the Y -axis (+ anterior, - posterior). The average local coordinate of the centroid of contact area for each flexion angle in the anatomic coordinate system was then determined using a coordinate transformation from the local x - y coordinate system to the anatomic X - Y coordinate system.

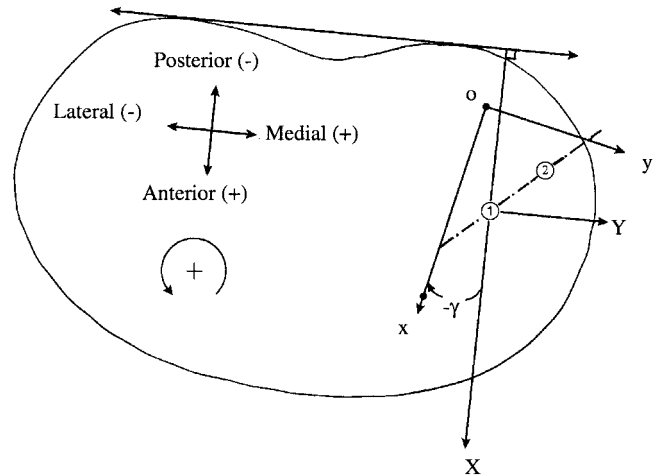


Figure B1. Diagram illustrating the local coordinate system (x, y) of the pressure-sensitive film and the anatomic coordinate system (X, Y) of the articular surface of the tibia. The origin of the local coordinate system on the pressure-sensitive film was the posterior pin mark (o), the x -axis was a line connecting the anterior and posterior pin marks (two black dots), the y -axis was a line drawn perpendicular to the x -axis at the origin. The origin of the anatomic coordinate system on the articular surface of the tibia was the centroid of the anatomic tunnel, the X -axis was a line drawn perpendicular to the Y -axis (+ anterior, - posterior), and the Y -axis was a line drawn connecting the posterior osteochondral junctions of the medial and lateral compartments (+ medial, - lateral). The average centroids of contact area for the anatomic tunnel (1) and a nonanatomic tunnel (2) are shown. A coordinate transformation was used to transform the centroid of contact area of the nonanatomic tunnel in the local coordinate system to the anatomic coordinate system using the two pin marks, which were registered on both the pressure-sensitive film and the digital photograph of the articular surface of the tibia.