Comparison of Kinematics and Tibiofemoral Contact Pressures for Native and Transplanted Lateral Menisci

Patrick C. McCulloch,*† MD, Donald Dolce,† MD, Hugh L. Jones,‡ BS, Andrea Gale,† MD, Michael G. Hogen,‡ BA, Jason Alder,‡ MD, Jeremiah E. Palmer,† MD, and Philip C. Noble,‡ PhD
Investigation performed at Houston Methodist Hospital, Houston, Texas, USA

Background: Lateral meniscus transplantation is a proven treatment option for the meniscus-deficient knee, yet little is known about meniscal kinematics, strain, and tibiofemoral contact pressure changes after transplantation or the effect of altered root position in lateral meniscus transplantation.

Purpose: To compare the native lateral meniscal kinematics, strain, and tibiofemoral contact pressures to a best-case scenario meniscus transplant with perfectly matched size and position and to determine how sensitive these factors are to subtle changes in shape and position by using a nonanatomic meniscus transplant position.

Study Design: Controlled laboratory study.

Methods: The lateral menisci of 8 cadaveric knees were circumferentially implanted with radiopaque spherical markers. They were mounted to a testing apparatus applying muscle and ground-reaction forces. The meniscus was evaluated at 0°, 30°, 90°, and 115° of knee flexion using Roentgen stereophotogrammetric analysis (RSA), with a pressure sensor affixed to the lateral tibial plateau. Measurements were recorded for 3 states: the native lateral meniscus, an anatomic autograft transplant, and a nonanatomic autograft transplant with an anteriorized posterior root position.

Results: After transplantation, there was less posterior displacement in both the anatomic and nonanatomic transplant states compared with the native meniscus, but this was not significant. The largest lateral translation in the native state was 2.38 ± 1.58 mm at the anterolateral region from 0° to 90°, which was increased to 3.28 ± 1.39 mm ($P = .25$) and 3.12 ± 1.18 mm ($P = .30$) in the anatomic and nonanatomic transplant states, respectively. Internal deformations of the transplant states were more constrained, suggesting less compliance. The native meniscus distributed load over 223 mm^2, while both the anatomic (160 mm^2) and nonanatomic (102 mm^2) states concentrated pressure anteriorly to the tibial plateau centroid.

Conclusion: This study is the first to characterize kinematics in the native lateral meniscus compared with a transplanted state utilizing RSA. Results demonstrate increased meniscal constraint and pressure concentrations even after an ideal size and position matched transplantation, which further increased with a nonanatomic posterior root position.

Clinical Relevance: The results show that kinematics are similar in both transplanted states when compared with the native meniscus at various flexion angles. Because both transplanted states were more constrained with less deformation compared with the native state, this should allow for relatively safe postoperative range of motion. However, in the transplanted states, peak pressures were distributed over a smaller area and shifted anteriorly. This pattern was exacerbated in the nonanatomic state compared with anatomic. This could have detrimental effects with regard to articular cartilage degeneration, and ultimately result in a failed transplantation.

Keywords: meniscus; knee; meniscus transplantation; meniscal kinematics; strain

Total and subtotal meniscectomies increase the resultant forces seen on the tibiofemoral compartment articular cartilage and can lead to progressive arthritic changes in the respective compartment.[3,4,9] Meniscal transplantation has been shown to reduce pain, decrease knee effusions, and improve functional scores in patients with prior meniscectomy.[14] The goal of treating a meniscus-deficient knee is to provide symptomatic relief in the short term, with longer term restoration of form and function.[10]

Though meniscus transplantation improves contact mechanics, it does not restore biomechanical function to normal levels.[11] This may be due to several factors, including both graft size and position. Obtaining a perfectly size-matched allograft for use in meniscus transplantation can be challenging. If the donor meniscus is slightly larger or smaller than the recipient's native meniscus, the roots will

The Orthopaedic Journal of Sports Medicine, 4(12), 2325967116674441
DOI: 10.1177/2325967116674441

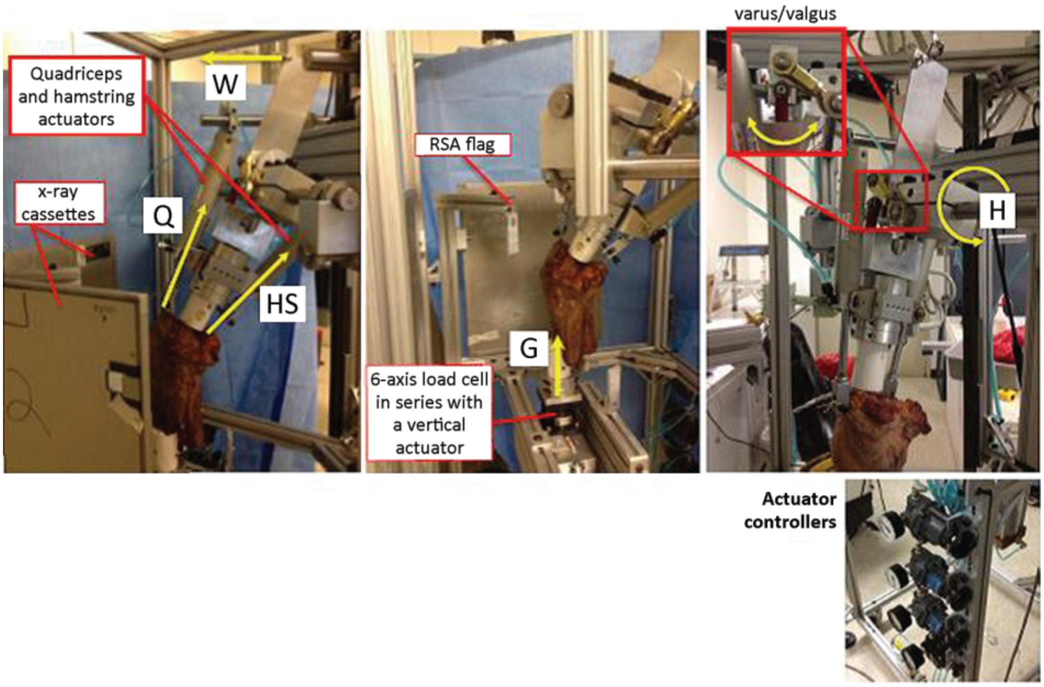

Figure 1. Custom testing apparatus capable of independently loading muscle groups and delivering ground-reaction forces during a simulated squatting. G, ground-reaction force; H, hip joint reaction; HS, hamstring force; Q, patellar tendon force; RSA, Roentgen stereophotogrammetric analysis; W, anterior force.

be in a nonanatomic position. One of the purported advantages of the use of a bone bridge technique is that it maintains the correct spatial relationship between the roots.[12] This may be especially difficult to do if a soft tissue–only meniscus transplantation is performed, which is favored by some authors.[25]

Furthermore, exact positioning of the meniscus transplant in the knee can be challenging, and nonanatomic root position can be detrimental to the goals of transplantation. Several studies have investigated the effect of root position in medial meniscus transplantation, demonstrating increased degenerative changes and adverse changes in contact pressures with nonanatomic root position.[20,21,26] These studies are important because the posterior root position, especially with independent soft tissue or bony plugs in the setting of intact cruciate ligaments, is difficult to place as the surgeon's view of the anatomic insertion point can be obscured. No studies to date have examined the effect of nonanatomic positioning in lateral meniscus transplantation.

The aim of this study was to measure the meniscal kinematics and contact forces during simulated weightbearing and knee flexion in a cadaveric native lateral meniscus and in a "best-case scenario" transplantation model by explanting and reimplanting the lateral meniscus with a bone bridge after registering its native position in the knee. This provided an exact size and position match for an ideal transplant. In addition to comparing the native meniscus to an anatomically placed transplant, a nonanatomic transplant was also tested using a common alteration in posterior root position to determine how sensitive these variables were to a subtle change in root position and meniscal shape.

METHODS

Eight fresh-frozen human lower limbs with a mean age of 48 years (range, 38-58 years; 7 male, 1 female) were arthroscopically inspected to ensure the menisci and lateral chondral surfaces were free of traumatic and degenerative defects. The knees were resected 20 cm from the joint line proximally and distally, stripped of skin, and potted using casting resin (Smooth-Cast 300; Smooth-On) and polyvinyl chloride (PVC) piping. A custom testing apparatus capable of independently loading muscle groups and delivering ground-reaction forces during a simulated squatting maneuver was constructed (Figure 1). When mounted, the tibial axis was perpendicular to the floor and the femur was attached to a loading head that allowed translational and rotational freedom. Isolated

*Address correspondence to Patrick C. McCulloch, MD, Houston Methodist Orthopedics & Sports Medicine, Outpatient Center, 6445 Main Street, Suite 2500, Houston, TX 77030, USA (email: pcmcculloch@houstonmethodist.org).
†Houston Methodist Orthopedics & Sports Medicine, Houston Methodist Hospital, Houston, Texas, USA.
‡Institute of Orthopedic Research & Education, Houston, Texas, USA.
The authors declared that they have no conflicts of interest in the authorship and publication of this contribution.
Ethical approval for this study was waived by The Methodist Hospital Research Institute.

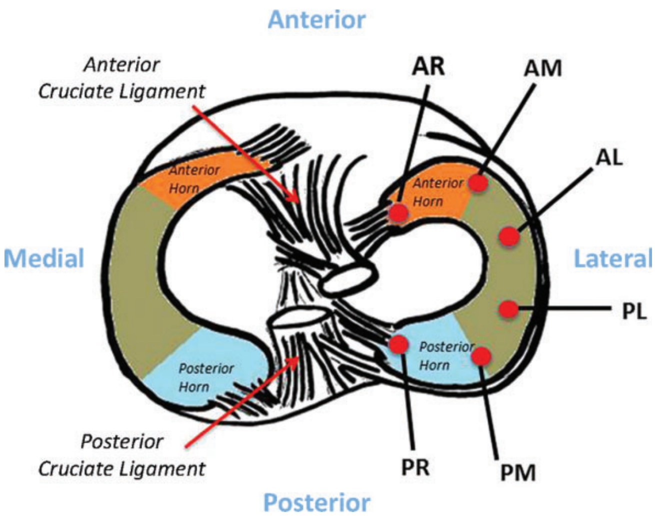

Figure 2. Bead locations for kinematic tracking during Roentgen stereophotogrammetric analysis testing included the following positions: anterior root (AR), anteromedial (AM), anterolateral (AL), posterolateral (PL), posteromedial (PM), and posterior root (PR).

muscle leads from the hamstrings and quadriceps were individually attached to pneumatic actuators,[1,19] with a tibial pneumatic actuator delivering a ground-reaction force.

The lateral meniscus was circumferentially implanted with 6 spherical markers of different size and density (0.8 mm tantalum, 1.0 mm tantalum, and 1.0 mm stainless steel) to allow for kinematic tracking during Roentgen stereophotogrammetric analysis (RSA) testing.[16,22] The positions included anterior root, anteromedial (AM), anterolateral (AL), posterolateral (PL), posteromedial (PM), and posterior root (Figure 2). The meniscus was accessed through a lateral parapatellar incision and a 1-cm PL capsular incision; custom syringe needles, guides, and rods were used to pierce the meniscus in the peripheral one-third and fix the markers 1 mm below the meniscus surface with cyanoacrylate. Reference markers were implanted in the femoral epicondyles and tibial metaphysis.

Tekscan pressure film sensors were inserted between the lateral meniscus and tibial plateau. The sensor lead extended through a 3.0-cm transverse incision made lateral to the patellar ligament beneath the anterior portion of the lateral meniscus; the arthrotomy incisions were sutured prior to Tekscan testing. Guide probes were used to activate the sensor, through three 2.5-mm portals created in the anterior tibia and allowed registration and localization of the data map. This allowed for reproducible results for each testing state, utilizing the registered probe positions to ensure correct positioning of the Tekscan pressure data. Although no sensor drift or damage occurred during testing, new sensors were used for each specimen. The 3-dimensional (3D) laser-scanned models of each lateral plateau were used for data analysis for each specimen, with an averaged composite plateau created for the final comparative analysis.

The meniscus autograft was harvested through the anterior parapatellar and PL incisions; the meniscocapsular

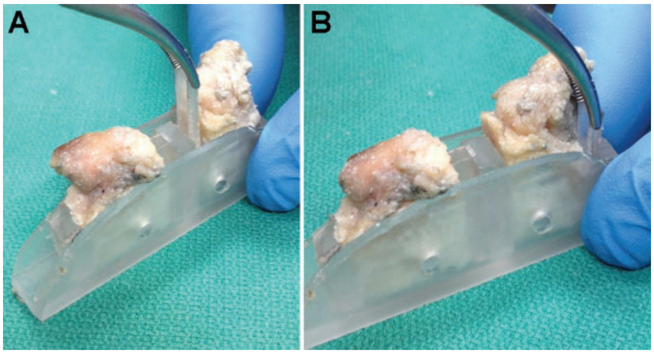

Figure 3. Depiction of the polycarbonate cassette and shim system used to (A) hold the bone block and (B) change the root position. The meniscus has been removed to allow better visualization.

attachments were incised, and a reciprocating saw blade was used to cut a 1 × 1–cm trough, which included the anterior and posterior roots. The bone block was water pick–blasted and dried with 70% ethanol to remove lipids, plasticized to add strength, and seated in a machined polycarbonate cassette (Figure 3A). Meniscal tissue was unaltered. The cassette exactly matched the tibial bone block geometry when seated, which ensured exact anatomic placement when the cassette was flush with the anterior tibial cortex. Precisely 5 mm of bone between the roots was excised and replaced with a matching polycarbonate shim. This allowed for anteriorization of the posterior root with removal of the shim and placement of the shim behind the posterior root for the nonanatomic testing state (Figure 3B). The meniscus was reimplanted using cyanoacrylate to affix the bone block cassette in the trough; peripherally, 2-0 FiberWire meniscal repair needles (Arthrex) and meniscal dart sheaths were used to suture the meniscus to the capsule with a vertical mattress technique utilizing 6 mattress sutures per specimen with an additional outside-in anterior horn vertical mattress suture. These sutures remained in place during different testing states. Care was taken to avoid placing sutures in the popliteus tendon in the popliteal hiatus.

Before testing, specimen tissue was preconditioned with 3 full flexion-extension cycles. On testing, the specimens had biplanar radiographic imaging and pressure map recordings at flexion angles of 0°, 30°, 90°, and 115°. A ground-reaction force of 267 N, one-third scaled body weight of 36.3 kg, was applied to the distal tibia, and scaled loads of 218 and 80 N were applied to the quadriceps and hamstrings, respectively. We chose an average adult body weight and used a scaled-down percentage of this weight for our ground-reaction force to preserve the cadaveric specimens during the multiple testing states.

In each loading position, the 3D location of each implanted marker was measured using RSA. Dual film cassettes, subtended 90°, were mounted to the testing frame, and X-ray tubes were positioned normal to each cassette center at a distance of 1.3 m. A calibration flag, having known spatial coordinates with respect to each film cassette via laser scanning (Faro Technologies UK Ltd), was fixed to the frame to

TABLE 1
Mean Lateral Translation of Each Region in Different Meniscal States[a]

	Lateral Translation, mm					
Flexion angle, deg	Anterior Root	Anteromedial	Anterolateral	Posterolateral	Posteromedial	Posterior Root
Native meniscus						
0-30	0.24 ± 0.63	−0.18 ± 0.91	1.13 ± 1.04	0.59 ± 1.63	−1.35 ± 1.87	−0.58 ± 0.89
30-90	0.24 ± 0.64	0.61 ± 1.53	1.24 ± 1.69	−0.31 ± 1.41	−1.11 ± 2.67	0.03 ± 1.62
90-115	−0.08 ± 0.04	−0.38 ± 0.76	−0.91 ± 1.28	−0.67 ± 1.15	−1.41 ± 1.49	−0.84 ± 0.90
0-115	0.41 ± 1.17	0.05 ± 2.04	1.47 ± 2.68	−0.39 ± 2.61	−3.86 ± 4.03	−1.39 ± 2.08
Anatomic transplant						
0-30	0.70 ± 1.05	0.98 ± 1.74	1.64 ± 1.68	−0.71 ± 1.75	−1.32 ± 1.24	−1.00 ± 0.88
30-90	0.26 ± 1.36	0.37 ± 1.63	1.64 ± 2.21	0.67 ± 2.32	0.13 ± 2.31	0.68 ± 0.91
90-115	0.11 ± 0.79	−0.06 ± 1.27	−0.58 ± 1.50	−1.18 ± 1.32	−1.39 ± 1.21	−0.54 ± 0.94
0-115	1.07 ± 1.46	1.30 ± 2.07	2.69 ± 2.37	−1.23 ± 4.15	−2.59 ± 3.97	−0.86 ± 1.48
Nonanatomic transplant						
0-30	0.25 ± 0.94	0.40 ± 1.25	1.42 ± 1.48	−0.06 ± 1.50	−1.16 ± 0.85	−0.71 ± 0.99
30-90	0.30 ± 1.14	0.76 ± 1.44	1.71 ± 1.96	0.16 ± 2.80	−0.02 ± 2.08	0.48 ± 1.07
90-115	0.42 ± 1.36	0.39 ± 2.04	−0.56 ± 2.60	−1.93 ± 1.18	−2.03 ± 0.94	−0.92 ± 1.02
0-115	0.98 ± 1.98	1.55 ± 2.54	2.56 ± 3.18	−1.83 ± 3.31	−3.21 ± 3.02	−1.14 ± 1.21

[a]Data are reported as mean ± SD. There were no statistically significant differences when compared with the native state ($\alpha = 0.05$).

allow 3D triangulation of the X-ray source. On testing, biplanar exposures were taken and digitized with a Microtek Medi-6000 scanner (Microtek Lab Inc) at 600 dpi. A threshold routine determined the 2D coordinates of all marker centers on each film with respect to their origins using Image J software (National Institutes of Health). These coordinates, combined with the triangulated X-ray source positions, were used to calculate 3D spatial locations for each fiduciary and meniscal marker using custom software script (MatLab) to an accuracy of better than 80 μm based on default software precision computations. The 3D coordinates were imported into modeling software (RapidForm; 3D Systems), where data from every flexion angle were overlaid onto 1 tibia via registration of the mentioned tibial fiduciaries. These computer models, consisting of 1 tibia and multiple transitioning menisci per flexion angle, were used to measure the marker displacements. The change in marker translation and regional deformation were then averaged and compared for each specimen state at each flexion angle. The average marker positions were then plotted, using an anatomic coordinate system in the transverse and sagittal plane for each testing state and flexion angle.

Statistical Analysis

The mean values between groups were compared using repeated-measures analysis of variance (ANOVA). Level of significance was set at .05, and Fisher least significant difference comparisons were performed for all findings. All statistical analyses were performed using SPSS v. 20.0 software (IBM Corp).

RESULTS

When comparing translation of the native meniscus in all 3 axes to the anatomic and nonanatomic transplants, there were no statistically significant differences. Comparisons of the mean translation data for each meniscal state are presented in Tables 1 through 3. There was, however, a significant increase in posterior translation of the lateral femoral condyle during flexion, with an average of 23.3 mm in the native state compared with 19.3 mm in the transplanted state ($P = .04$). The transition from full extension to 30° was similar between states, but the native state demonstrated significantly greater posterior translation from 30° to 90° of flexion (10.3 vs 6.74 mm; $P = .02$).

Native Lateral Meniscus Kinematics

During knee flexion, the native lateral meniscus translated posteriorly with combined internal elongation and constrictive deformations. The largest overall posterior translation was seen in the AM and AL regions with almost half of the translation occurring from full extension to 30° of flexion; the AM region had more translation than the corresponding PM region ($P = .003$). Of the posterior regions, the PL region had the most overall posterior translation, with the most displacement occurring during the transition from 0° to 30° of flexion. With increasing flexion, the AL/PL regions contracted by 1.34 mm, causing the AM/AL and PM/PL regions to elongate (0.46 and 0.92 mm, respectively). While the anterior body had more posterior displacement with flexion, the posterior meniscal body had more vertical elevation with increasing flexion; the PM region averaged significantly greater elevation than the AM meniscus ($P = .001$).

Anatomic and Nonanatomic Meniscal Transplant Kinematics

The transplanted states displayed more constrained kinematics compared with the native meniscus (Figure 4). The

TABLE 2
Mean Posterior Translation of Each Region in Different Meniscal States[a]

	Posterior Translation, mm					
Flexion angle, deg	Anterior Root	Anteromedial	Anterolateral	Posterolateral	Posteromedial	Posterior Root
Native meniscus						
0-30	2.21 ± 2.19	5.88 ± 4.15	4.47 ± 5.10	3.22 ± 3.69	1.89 ± 3.02	1.09 ± 1.77
30-90	2.16 ± 3.46	3.17 ± 4.91	3.84 ± 5.12	2.62 ± 3.08	2.33 ± 2.82	0.12 ± 1.67
90-115	1.10 ± 1.83	2.15 ± 1.65	2.82 ± 1.97	1.60 ± 1.39	1.61 ± 0.91	0.93 ± 0.61
0-115	5.47 ± 5.99	11.20 ± 4.81	11.13 ± 3.86	7.45 ± 4.24	5.83 ± 2.71	2.13 ± 1.69
Anatomic transplant						
0-30	2.09 ± 2.90	4.51 ± 5.38	3.66 ± 5.67	2.46 ± 5.13	1.30 ± 4.19	0.81 ± 1.89
30-90	1.36 ± 3.24	0.70 ± 4.69	−0.18 ± 4.97	0.09 ± 3.32	−0.06 ± 2.31	−0.56 ± 1.04
90-115	1.09 ± 1.33	2.77 ± 1.76	3.45 ± 2.07	2.52 ± 2.28	1.93 ± 1.82	0.51 ± 1.00
0-115	4.55 ± 6.51	7.98 ± 7.95	6.92 ± 7.29	5.07 ± 4.47	3.16 ± 3.59	0.76 ± 2.27
Nonanatomic transplant						
0-30	2.29 ± 2.73	4.88 ± 4.08	3.57 ± 4.34	2.32 ± 4.39	1.35 ± 3.75	0.48 ± 1.20
30-90	1.19 ± 2.99	0.88 ± 3.87	0.27 ± 4.00	0.90 ± 2.47	0.44 ± 1.76	−0.31 ± 0.74
90-115	1.64 ± 2.05	3.78 ± 2.56	4.80 ± 3.02	3.73 ± 3.40	2.73 ± 2.46	0.96 ± 0.80
0-115	5.12 ± 6.00	9.54 ± 6.63	8.63 ± 5.95	6.94 ± 4.16	4.52 ± 2.93	1.13 ± 1.32

[a]Data are reported as mean ± SD. There were no statistically significant differences when compared with the native state ($\alpha = 0.05$).

TABLE 3
Mean Elevation of Each Region in Different Meniscal States[a]

	Vertical Translation, mm					
Flexion angle, deg	Anterior Root	Anteromedial	Anterolateral	Posterolateral	Posteromedial	Posterior Root
Native meniscus						
0-30	−1.02 ± 0.95	−1.24 ± 1.24	0.36 ± 2.02	1.78 ± 1.74	3.09 ± 2.23	1.62 ± 1.21
30-90	−0.04 ± 0.33	0.85 ± 1.22	1.92 ± 1.49	1.67 ± 2.64	2.30 ± 2.70	0.35 ± 1.73
90-115	−0.42 ± 0.31	0.30 ± 1.00	0.97 ± 1.03	0.70 ± 1.48	1.69 ± 1.17	0.41 ± 0.73
0-115	−1.48 ± 1.05	−0.10 ± 0.98	3.25 ± 1.71	4.15 ± 2.72	7.08 ± 3.87	2.39 ± 2.25
Anatomic transplant						
0-30	−1.17 ± 1.79	−1.28 ± 1.57	1.62 ± 1.44	3.63 ± 3.48	3.54 ± 2.90	2.14 ± 1.54
30-90	−0.03 ± 1.40	0.33 ± 1.83	0.49 ± 1.61	0.34 ± 2.95	0.44 ± 2.40	−0.09 ± 0.71
90-115	0.12 ± 0.76	0.74 ± 0.90	1.12 ± 0.83	1.90 ± 1.52	1.72 ± 1.32	0.89 ± 0.88
0-115	−1.09 ± 1.16	−0.21 ± 2.43	3.24 ± 3.18	5.88 ± 3.81	5.70 ± 3.79	2.94 ± 1.39
Nonanatomic transplant						
0-30	−1.15 ± 1.50	−1.77 ± 1.69	1.54 ± 1.32	2.74 ± 2.67	2.85 ± 2.31	1.13 ± 1.22
30-90	−0.02 ± 0.93	0.87 ± 2.11	0.95 ± 2.06	0.84 ± 2.16	0.58 ± 1.81	−0.20 ± 0.62
90-115	−0.10 ± 0.37	0.76 ± 0.46	1.14 ± 0.53	2.04 ± 1.37	1.71 ± 1.20	0.69 ± 0.62
0-115	−1.27 ± 0.96	−0.13 ± 1.51	3.63 ± 2.74	5.63 ± 2.52	5.15 ± 2.55	1.62 ± 1.24

[a]Data are reported as mean ± SD. There were no statistically significant differences when compared with the native state ($\alpha = 0.05$).

overall posterior translation of the AM and AL regions was reduced in the anatomic and nonanatomic states. Translation of the posterior regions decreased as well. However, none of these differences were significant. When observing the complete range of motion, regional elongation and constrictive deformation were minimal for each transplanted state when compared with the native, especially in the AL/AM and PL/PM regions. The amount of lateral translation did increase in the transplanted states, but again, these changes did not reach significance. Marker separation was decreased throughout the entire meniscus in the transplanted states, indicating less internal deformation (see Figure 5 and the Video Supplement).

Contact Pressure Measurements

Comparisons of the contact pressures maps are seen in Figure 6. Values are presented in Table 4. The native meniscus distributed tibiofemoral contact pressures over a large portion of the tibial plateau. They were evenly distributed over the anterior and central portions of the plateau, with the highest peak pressures seen posteriorly. Both transplanted states also displayed greater peak pressures as the load was distributed over a smaller area. This was shifted to the anterior portion of the plateau in both transplanted states. Although not statistically significant, the nonanatomic transplant resulted in the smallest area of distribution, the

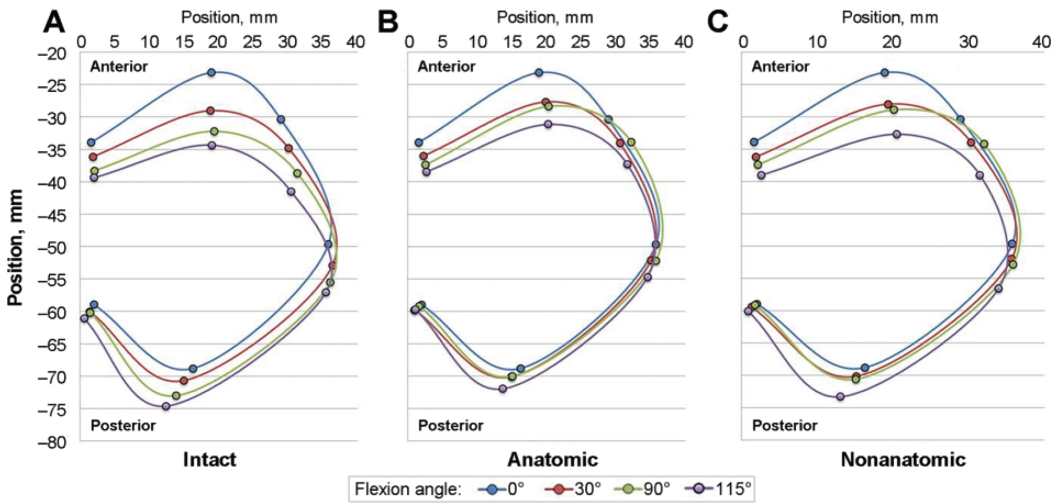

Figure 4. The (A) intact and (B) anatomic transverse plane translation and (C) nonanatomic transverse motion revealed that the transplanted states displayed more constrained kinematics compared with the native meniscus.

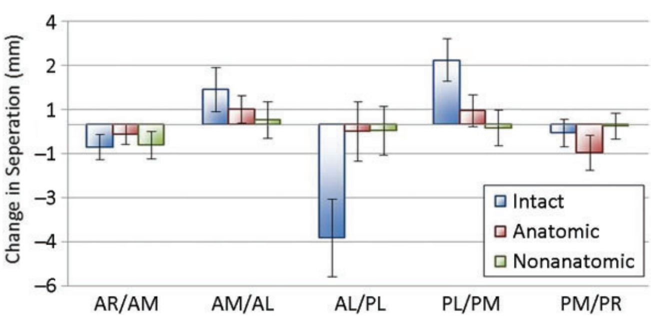

Figure 5. Change in marker separation from 0° to 115° of flexion, transverse plane: intact, anatomic, and nonanatomic. AL, anterolateral; AM, anteromedial; AR, anterior root; PL, posterolateral; PM, posteromedial; PR posterior root.

greatest peak forces, and the greatest shift anteriorly compared with both the native and anatomic state.

DISCUSSION

The purpose of this study was to define the normal kinematics of the lateral meniscus during weightbearing and range of motion with the use of RSA and to measure the lateral tibiofemoral contact distribution pressures before and after meniscal transplantation. The second phase of the project compared a best-case scenario lateral meniscal transplant with a perfect anatomic size and position match to a nonanatomic transplant by slightly altering the posterior root to a more anterior position to determine how sensitive these variables are to subtle changes in shape and position of the transplanted meniscus.

When comparing the anatomic transplant with the native lateral meniscus kinematics, the anatomic transplant had similar behaviors for translation and deformation in response to knee flexion. However, it did exhibit a more constrained pattern of motion with decreased posterior translation of all regions in the transplanted state. Furthermore, contact pressures in the transplanted state were concentrated over a smaller area, with greater peak pressures directed anteriorly over the tibial plateau. These changes demonstrate abnormal function of the transplanted meniscus despite a best-case scenario size and position match, which may adversely affect the goals of transplantation including chondral protection.

When comparing the anatomic transplant to the nonanatomic transplant with the posterior root in a more anterior position, the kinematics were not significantly changed. Translation and deformation were similar, but this was again more constrained than the kinematics of the native meniscus. Interestingly, the degree of translation in the nonanatomic transplant was closer to values seen in the native meniscus; however, the nonanatomic transplant resulted in even greater concentration of contact pressures than the anatomic transplant. These concentrated pressures were again directed anteriorly and would be expected to adversely affect the chondral surfaces in this region over time.

Several studies have examined the kinematics of the native lateral meniscus. Vedi et al[23] examined meniscal translation in healthy volunteers while weightbearing from full extension to 90° of flexion in vivo using open magnetic resonance imaging (MRI) and found the anterior horn of the lateral meniscus translates posteriorly 9.5 mm while the posterior horn translates 5.6 mm. This is comparable to our findings of posterior translation of 9.05 mm at the AM and 5.22 mm at the PM with only one-third average body weight. When Vedi et al[23] examined nonweightbearing, the anterior horn of the lateral meniscus demonstrated the most significant change with a decrease in translation to 6.3 mm. Epler et al[8] used MRI to examine movement of healthy menisci from 0° to 120° and found the lateral meniscus anterior horn translated 7.5 mm posteriorly and the posterior horn translated 6.2 mm under nonweightbearing

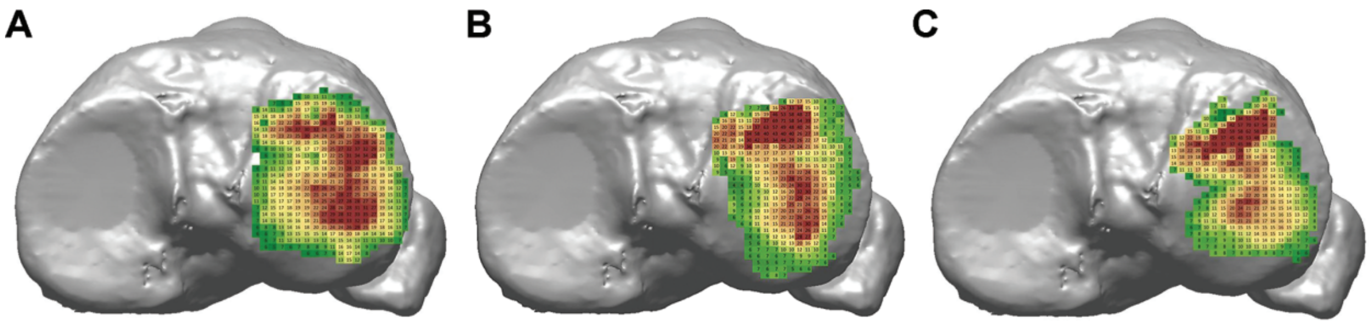

Figure 6. Three-dimensional computer models showing (A) intact pressure distribution, (B) anatomic pressure distribution, and (C) nonanatomic pressure distribution over the tibial plateau. The graded color map shows the pressure from low (green) to high (red). The top 10% is shown in red, the middle 50% in yellow, and the bottom 10% in green.

TABLE 4
Contact Pressure Values and Area of Distribution in Different Meniscal States

	Area of Distribution, mm^2	Anterior Peak Pressure, kPa	Central Peak Pressure, kPa	Posterior Peak Pressure, kPa	Mean Peak Pressure, kPa
Native meniscus	223	173.1	173.8	188.9	178.6
Anatomic transplant	160	250.3	166.2	168.9	195.1
Nonanatomic transplant	102	275.1	170.3	145.5	197.2

conditions. Poynton et al looked specifically at the posterior horn of the lateral meniscus in cadaveric knees and found that from 0° to 120°, the posterior horn translated posteriorly, medially, and superiorly.[18] With sectioning of the meniscofemoral ligaments, medial and superior translation was decreased while posterior translation increased.

The native meniscus in our study distributed pressure over the entire tibial plateau, while the transplant states were more consolidated with increased pressure concentrations anterior to the plateau centroid. McDermott et al[17] studied cadaveric knee pressure mapping after meniscectomy and with different lateral meniscal allograft fixation techniques and found pressures decreased to near normal states after allograft transplantation. Their study did not formally size-match the meniscal allografts, and the mean age of their specimens was 89 years, with all specimens having preexisting moderate to severe chondral changes. Other studies dealing with medial meniscal transplantation have revealed higher than normal pressures and altered pressure distribution patterns.[2,11,13] Our study used younger specimens than the study by McDermott et al,[17] with autograft transplants to avoid size-match variations.

Graft extrusion, or radial displacement, is a common finding in meniscal transplants and has been linked to oversized allografts.[24] This was eliminated in our study by the use of a lateral meniscal autograft rather than attempting to size-match a lateral meniscal allograft, which is a novel technique that we have developed. Oversized lateral meniscal allografts have led to increased forces across the articular cartilage, whereas undersized allografts have resulted in normal forces across the articular cartilage but greater forces across the meniscus; allografts less than 10% smaller or larger than the original menisci had graft and articular cartilage pressures similar to intact knees.[7] Radial displacement of the meniscus is considered significant if the distance between the tibial plateau and the outer edge of the meniscus exceeds 3 mm as it can no longer protect the underlying cartilage.[6] Our study showed that the largest lateral excursion occurred at the anterolateral bead position with 0° to 90° of flexion and with 2.4 mm of movement in the native meniscus, increasing by 0.9 mm and 0.7 mm in the anatomic and nonanatomic transplants, respectively, which did not approach significant extrusion values.

Choi et al[5] postoperatively evaluated 33 consecutive lateral meniscal transplants at 6 months using MRI and reported a mean meniscus allograft extrusion past the edge of the tibial plateau of 3.2 ± 2.3 mm. The extrusion amount correlated with the center and anterior portion of the bony trough of the graft (mean, 42.3% from the outer edge of the lateral tibial plateau). They found that less extrusion occurred if the center of the graft's bony bridge was located more medial and approached the midline of the tibial plateau. Yoon et al[27] evaluated MRIs at 1 year after surgery for meniscal extrusion in 11 consecutive lateral meniscal transplants and found a mean extrusion of only 1.6 mm. Their study utilized a transpatellar tendon guide pin insertion and the keyhole method for their meniscal transplants rather than the more traditional parapatellar method, and they believed larger reported extrusions in other studies were due to a lateralized posterior root position resulting from difficulties in positioning an anterior cruciate ligament targeting guide around the lateral aspect of the patellar tendon. In a similar study, Lee et al[15] found that graft extrusion increased as the axial plane trough angle increased relative to the interspinal groove with MRI evaluation. An increased trough angle essentially lateralizes the posterior root of the meniscal graft and caused increases in graft extrusion. In our model, the meniscal root locations were precisely reproduced in the anatomic transplant state. There was less than 1 mm of increased lateral translation, which is likely attributable to increased meniscal constraint of the anterior and posterior meniscus due to capsular fixation, which prevented the natural lateral elongation seen with knee flexion.

Graft deformation was surprisingly lower in both transplanted states, with more compression than distraction with the anteriorized root. We concluded that this decreased deformation related to the more stable posterior portion of the lateral meniscus through the range of motion, with the increased posterior and superior motion at higher degrees of flexion in the native meniscus leading to increased deformation. Decreased deformation with flexion in the transplanted meniscus may allow for increased postoperative flexion with minimal risk to the graft.

Limitations of this study included the potential for altered meniscal mechanics from entering and manipulating the lateral compartment during the RSA bead implantation and Tekscan insertion; we attempted to minimalize this with closure of the capsule prior to testing. Though using a meniscal autograft eliminated the potential for size mismatch, the compliance of the tissue potentially could have been altered. We tried to minimize this by storing the meniscus in a sealed bag with a moist wrap or in the joint once reimplanted. Though the knee was previously frozen and thawed prior to testing, there was no additional cellular alteration of the meniscal tissue, which may have further propagated shrinkage such as with lyophilized grafts. The meniscal states were also tested only 267 N of ground-reaction force, equal to 33% of an average body weight, which may have limited kinematic differences between the tested states. This study looked only at lateral meniscus transplant using a bone-block technique and the kinematics immediately following, so the findings may not be applicable to medial meniscus transplants or any long-term clinical changes for lateral meniscus transplants. Also, technical limitations of set up did not allow for randomization of testing order among the states. Future work that examines the effect of additional alterations in meniscal transplant position should consider this to account for changes that may occur over the course of testing.

Additionally, this study represents an ideal state of meniscal transplant in which the transplanted meniscus is exactly the appropriate size for the recipient knee. By using an autograft, we were able to eliminate the sizing mismatches that are commonly found in practice. As such, the results of this study represent the best possible results and may not be achievable clinically.

CONCLUSION

Meniscal transplantation is a frequently employed option for the younger patient with meniscal deficiency to slow degenerative changes within the respective compartment in the knee. This study is the first to use RSA for the evaluation of native and transplanted lateral meniscal kinematics during knee range of motion. Though lateral meniscal transplantation has been shown to improve joint contact pressures when compared with total meniscectomy, our study found that it does not reestablish normal meniscal kinematics or tibiofemoral contact pressures but rather shifts the contact pressures anteriorly and constrains the posterior motion and the natural rollback of the meniscus during knee flexion. Anteriorizing the posterior root position did not produce significant differences when compared with an anatomically correct posterior root position with regard to meniscal translation.

A Video Supplement for this article is available at http://journals.sagepub.com/doi/suppl/10.1177/2325967116674441.

REFERENCES

1. Ahmed AM, Burke BL, Hyder A. Force analysis of the patellar mechanism. *J Orthop Res*. 1987;5:69-85.
2. Alhalki MM, Hull ML, Howell SM. Contact mechanics of the medial tibial plateau after implantation of a medial meniscal allograft: a human cadaveric study. *Am J Sports Med*. 2000;28:370-376.
3. Allen PR, Denham RA, Swan AV. Late degenerative changes after meniscectomy: factors affecting the knee after operation. *J Bone Joint Surg Br*. 1984;66:666-671.
4. 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;14:270-275.
5. Choi CJ, Choi YJ, Lee JJ, Choi CH. Magnetic resonance imaging evidence of meniscal extrusion in medial meniscus posterior root tear. *Arthroscopy*. 2010;26:1602-1606.
6. Choi NH, Yoo SY, Victoroff BN. Position of the bony bridge of lateral meniscal transplants can affect meniscal extrusion. *Am J Sports Med*. 2011;39:1955-1959.
7. 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.
8. Epler M, Sitler M, Moyer R. Kinematics of healthy and meniscal repaired knees. *Res Sports Med*. 2005;13:91-109.
9. Fairbank TJ. Knee joint changes after meniscectomy. *J Bone Joint Surg Br*. 1948;30:664-670.
10. Hutchinson ID, Moran CJ, Potter HG, Warren RF, Rodeo SA. Restoration of the meniscus: form and function. *Am J Sports Med*. 2014;42:987-998.
11. Johannsen AM, Civitarese DM, Padalecki JR, Goldsmith MT, Wijdicks CA, LaPrade RF. Qualitative and quantitative anatomic analysis of the posterior root attachments of the medial and lateral menisci. *Am J Sports Med*. 2012;40:2342-2347.
12. Kang RW, Latterman C, Cole BJ. Allograft meniscus transplantation: background, indications, techniques, and outcomes. *J Knee Surg*. 2006;19:220-230.
13. Kim JG, Lee YS, Bae TS, et al. Tibiofemoral contact mechanics following posterior root of medial meniscus tear, repair, meniscectomy, and allograft transplantation. *Knee Surg Sports Traumatol Arthrosc*. 2013;21:2121-2125.
14. LaPrade RF, Wills NJ, Spiridonov SI, Perkinson S. A prospective outcomes study of meniscal allograft transplantation. *Am J Sports Med*. 2010;38:1804-1812.

15. Lee DH, Kim JM, Lee BS, Kim KA, Bin SI. Greater axial trough obliquity increases the risk of graft extrusion in lateral meniscus allograft transplantation. *Am J Sports Med*. 2012;40:1597-1605.
16. Lin DL, Ruh SS, Jones HL, Karim A, Noble PC, McCulloch PC. Does high knee flexion cause separation of meniscal repairs? *Am J Sports Med*. 2013;41:2143-2150.
17. McDermott ID, Lie DT, Edwards A, Bull AM, Amis AA. The effects of lateral meniscal allograft transplantation techniques on tibio-femoral contact pressures. *Knee Surg Sports Traumatol Arthrosc*. 2008;16: 553-560.
18. Poynton A, Moran CJ, Moran R, O'Brien M. The meniscofemoral ligaments influence lateral meniscal motion at the human knee joint. *Arthroscopy*. 2011;27:365-371.
19. Sakai N, Luo ZP, Rand JA, An KN. In vitro study of patella position during sitting, standing from squatting, and the stance phase of walking. *Am J Knee Surg*. 1996;9:161-166.
20. Sekaran SV, Hull ML, Howell SM. Nonanatomic location of the posterior horn of a medial meniscal autograft implanted in a cadaveric knee adversely affects pressure distribution on the tibial plateau. *Am J Sports Med*. 2002;30:74-82.
21. Stärke C, Kopf S, Gröbel KH, Becker R. The effect of a nonanatomic repair of the meniscal horn attachment on meniscal tension: a biomechanical study. *Arthroscopy*. 2010;26:358-365.
22. Tienen TG, Buma P, Scholten JG, van Kampen A, Veth RP, Verdonschot N. Displacement of the medial meniscus within the passive motion characteristics of the human knee joint: an RSA study in human cadaver knees. *Knee Surg Sports Traumatol Arthrosc*. 2005;13:287-292.
23. Vedi V, Williams A, Tennant SJ, Spouse E, Hunt DM, Gedroyc WM. Meniscal movement: an in-vivo study using dynamic MRI. *J Bone Joint Surg Br*. 1999;81:37-41.
24. Verdonk P, Depaepe Y, Desmyter S, et al. Normal and transplanted lateral knee menisci: evaluation of extrusion using magnetic resonance imaging and ultrasound. *Knee Surg Sports Traumatol Arthrosc*. 2004;12:411-419.
25. Verdonk PC, Demurie A, Almqvist KF, Veys EM, Verbruggen G, Verdonk R.Transplantation of viable meniscal allograft. Surgical technique. *J Bone Joint Surg Am*. 2006;88(suppl 1 pt 1):109-118.
26. von Lewinski G, Kohn D, Wirth CJ, Lazovic D. The influence of nonanatomical insertion and incongruence of meniscal transplants on the articular cartilage in an ovine model. *Am J Sports Med*. 2008;36: 841-850.
27. Yoon JR, Kim TS, Lee YM, Jang HW, Kim YC, Yang JH. Transpatellar approach in lateral meniscal allograft transplantation using the keyhole method: can we prevent graft extrusion? *Knee Surg Sports Traumatol Arthrosc*. 2011;19:214-217.