THE EFFECTS OF POSTERIOR TIBIAL MOBILIZATION ON MENISCAL MOVEMENT: AN IN-SITU INVESTIGATION

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ABSTRACT

Background: Anterior knee pain during knee extension may be related to a meniscal movement restriction and increased meniscal load during function. One method of treatment involves the use of manual posterior mobilization of the tibia to specifically target the meniscotibial interface of the knee joint.

Purpose: The purpose of this study was to measure motion at a cadaveric medial meniscus anterior horn during a posterior tibial mobilization.

Study Design: Prospective, multifactorial, repeated-measures laboratory study.

Methods: Eight unembalmed cadaveric knee specimens were mounted in a custom apparatus and markers were placed in the medial meniscus, tibia and femur. The tibia was posteriorly mobilized in two randomized knee positions (0 degrees and 25 degrees) using three randomly assigned loads (44.48N, 88.96N, and 177.93N). Markers were photographed and digitally measured and analyzed.

Results: All load x position conditions produced anterior displacement of the meniscus on the tibia, where the displacement was significant [$t(7) = -3.299$; $p = 0.013$] at 0 degrees loaded with 177.93N (mean 0.41 ± 0.35 mm). The results of 2(position) x 3(load) repeated measures ANOVA for meniscotibial displacement produced no significant main effects for load [$F(2,14) = 2.542$; $p = 0.114$] or position [$F(1,7) = 0.324$, $p = 0.587$]. All load x position conditions produced significant posterior tibial and meniscal displacement on the femur. The 2(position) x 3(load) repeated measures ANOVA revealed a significant main effect for load for both femoral marker displacement relative to the tibial axis [$F(2,14) = 77.994$; $p < 0.001$] and meniscal marker displacement relative to the femoral marker [$F(2,14) = 83.620$; $p < 0.001$].

Conclusion: Use of a mobilization technique to target the meniscotibial interface appears to move the meniscus anteriorly on the tibia. It appears that this technique may be most effective at the end range position.

Level of Evidence: 2 (laboratory study)

Keywords: Anterior knee pain, Knee, Meniscus

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INTRODUCTION

Anterior knee pain is a common patient complaint that can occur in response to several different pathologies including but not limited to intra-articular pathology, patellofemoral pain syndrome, plica syndrome, infrapatellar fat pad disorders, and apophysitis.¹⁻⁷ Treating anterior knee pain with limited knowledge of the specific pathology can give rise to variable responses and outcomes to common interventions.^{8,9} Pathology of the meniscus, particularly at the anterior horn, may produce anterior knee pain. Pereira et al¹⁰ and Mine et al¹¹ identified free nerve endings and nerve endings positive for substance P in the meniscus anterior horn, suggesting a pain-generating role. Moss et al¹² described an anterior knee pain management strategy aimed at the meniscus as the pain generator. These authors reported pain reduction when implementing a program that included mobilization to the meniscus. If the meniscus cannot sufficiently clear the anterior rolling femur in the closed kinematic chain, pain may result secondary to increased pressure on the anterior horn.

Orthopedic manual therapy (OMT) techniques designed to encourage meniscal movement between the femur and tibia have been proposed.^{3,13-15} Anterior meniscal translation on the tibia, resulting from OMT, can facilitate moving the meniscus out of the way of the anterior rolling femur during extension (Figure 1). Because the meniscus cannot be manually accessed in vivo in an isolated non-surgical fashion, clinicians can incorporate a manually-applied posterior mobilization force to the tibia in order to facilitate meniscal anterior displacement on the tibia. As the tibia and meniscus translate posterior during the posterior tibial mobilization, the meniscus is thought to come in contact with the femur, preventing further meniscal movement but allowing continued posterior tibial translation. In this case, the net effect would be a relative anterior meniscal displacement on the tibia (Figure 1). However, this mechanical response of the meniscus to manual posterior tibial mobilization has not been mechanically examined.

The purpose of this study was to measure motion at a cadaveric medial meniscus anterior horn (MMAH) during a posterior tibial mobilization. The

Figure 1. Selected component movements during knee extension and posterior tibial mobilization. Closed-chain knee extension produces anterior femoral swing (a), accompanied by anterior rolling (b) and posterior translation (c) of the femoral condyles, lending to potential MMAH compression (*) if the MMAH does not translate sufficiently anterior; During posterior tibial mobilization, a stabilization force (d) blocks the femur while a posterior tibial mobilization force (e) produces a posterior translation of the tibia, carrying the MMAH posterior until it comes in contact with the anterior femoral condyles (**). Further posterior tibial mobilization may result in anterior displacement of the MMAH (g) relative to the tibial plateau (f). A = Anterior; P = Posterior; F = Femur; T = Tibia; MMAH = Medial Meniscus, Anterior Horn.

investigators hypothesized that with a manually applied posterior tibial force with the femur posteriorly supported, the MMAH would significantly move anterior in relation to the tibia, accompanied by significant movement of the tibia in relation to the femur. Additionally, the investigators hypothesized that the MMAH would not move significantly with respect to the femur. This experiment incorporated the effects of two different knee angles and three different mobilization forces on MMAH motion.

METHODS

Design

The investigators implemented a prospective study using a 2 (knee position angle) x 3 (load intensity) multifactorial, repeated-measures design. The following dependent variables were evaluated:

1. Mensical Marker Displacement: Changes in perpendicular distance (mm) between the meniscal marker and the tibial axis.

2. Femoral Marker Displacement: Changes in perpendicular distance (mm) between the femur marker and the tibial axis.
3. Meniscal Minus Femur Marker Displacement: Changes in the difference between perpendicular distance (mm) of the MMAH marker to the tibial axis and femoral marker to the tibial axis.

The following independent variables were used in the study:

1. Knee position angle (two levels):
 - a. 0 degrees of flexion (0 deg)
 - b. 25 degrees of flexion (25 deg)
2. Load intensity (three levels):
 - a. 44.48 Newtons (44.48 N)
 - b. 88.96 Newtons (88.96 N)
 - c. 177.93 Newtons (177.93 N)

These independent variables produced a total of six load x position conditions:

- **Condition 1:** 0 deg 44.48 N = 0 degrees flexion, 44.48 Newtons load
- **Condition 2:** 0 deg 88.96 N = 0 degrees flexion, 88.96 Newtons load
- **Condition 3:** 0 deg 177.93 N = 0 degrees flexion, 177.93 Newtons load
- **Condition 4:** 25 deg 44.48 N = 25 degrees flexion, 44.48 Newtons load
- **Condition 5:** 25 deg 88.96 N = 25 degrees flexion, 88.96 Newtons load
- **Condition 6:** 25 deg 177.93 N = 25 degrees flexion, 177.93 Newtons load

Posterior tibial mobilization is commonly used to gain flexion of tibia on femur, as it promotes the appropriate arthrokinematic tibial translation occurring when the knee is actively flexed in the open kinematic chain.^{3,13,16} In addition, if the knee is placed in full available extension and the applied mobilization produces anterior meniscus displacement (as proposed in the present study), then a posterior tibial

mobilization could be suited for gaining full, pain-free knee extension.^{12,14} Thus, both fully extended (0 deg) and slightly flexed (25 deg) knee positions were incorporated to evaluate this effect and to respect changes in joint congruency that occur at the end of knee extension¹⁷⁻²⁰ on the proposed responses. Silvernail et al²¹ reported that approximately 45 N of posterior tibial force was required to create a Maitland grade III OMT maneuver aimed at restoring knee extension. Conversely, the present authors' pilot testing of mobilization forces that they clinically incorporate for treating the meniscotibial interface at end-range knee extension revealed that 177.93 N force was needed to reach end-range of posterior translation during the OMT mobilization technique under investigation. On that basis, the authors decided to use three different force values to measure a broader spectrum of responses: 44.48 N based on previous evidence²¹ regarding grade III Maitland mobilization; the present authors' preferred clinically force (177.93 N); and the 88.96 N value resting halfway between both the other two values.

Specimens

A total of eight cadaveric knee specimens were harvested from unembalmed cadavers that were previously donated by the local university willed body program. The average age of the specimens was 79 years. The specimens were previously stored at -80 degrees Fahrenheit, then thawed overnight to room temperature prior to experimental use. Cadaveric specimens were excluded if they demonstrated observable meniscal abnormalities or damage during visual inspection.

Instrumentation

Specimens were prepared by removing cutaneous and subcutaneous tissue to expose the bony regions while leaving the joint capsule-ligamentous and retinacular structures intact. A 1 cm x 1 cm tissue window was cut in the specimen's medial joint capsule to allow for visualization of the MMAH. A commercially available Phillips-type screw was inserted into the MMAH (meniscal marker). Additionally, Phillips-type screws were inserted into the distal medial femoral bone (femoral marker) and proximal medial tibia (tibial marker 1), each 5 cm from the medial joint line. Another Phillips-type screw was

Figure 2. *Posterior tibial mobilization in situ-grey arrow shows direction of mobilization force posterior on the tibia relative to the femur. Circles indicate the six reference points digitized for data analysis.*

placed 2 cm more distal on the medial tibia (tibial marker 2), allowing both tibial screws to create a reference line (tibial axis) for computing meniscal and femoral translations, as well as angular tibial motion all in the sagittal plane. Specimens were mounted in a custom wooden frame (Figure 2). The investigators insured that all markers and the ruler were positioned in the same plane to reduce error from differences in the depth of each image component. The wooden frame was securely attached to a table with clamps. The specimens were mounted in the frame by passing metal rods through the bony mid-shaft of both femur and tibia eight centimeters from the cut end of the bones. Bolts were used to secure the rods (not the bones) to the frame, which standardized the specimen position and minimized rotation in the transverse plane. The proximal end of the tibia remained completely unconstrained, so to allow a posterior mobilization force to create the observed tibial movements. The proximal end of the femur was secured with bolts but allowed positioning within the frame at either 0 deg knee flexion or 25 deg knee flexion. Knee position was measured with a standard goniometer. Stabilizing sandbags were positioned on the table, posterior to the distal femur.

The following principles were considered in order to ensure measurement validity during uniplanar image analysis: (1) the camera was aligned perpendicular to the testing plane, (2) sufficient focal

distance was maintained through all measurements, and (3) an object of known dimension was present within the field of view to be later used for calibration purposes.²² A standard ruler of 25 cm length was attached vertically to the tibial side of the wooden frame, which served as a coordinate and scaling reference during measurement (Figure 2). Marker displacement was photographed using a 6.3-megapixel digital camera (FinePix S7000, fujiFilm, Fuji Photo Film Co., Ltd. 26-30, Nishiazabu 2-chome, Minato-Ku, Tokyo 106-620, Japan) and a room light source. The camera was placed one meter from the plane of the previously described ruler, with the focal point parallel to and centered with the specimen's medial joint line. The camera was manually focused before image capture of each specimen. The marker position was captured and digitally analyzed (digitized) using uniplanar image analysis methods that have previously demonstrated reliability (intra- and inter-tester) and validity for measuring structural relationships and responses at different joint locations in different controlled laboratory settings.²³⁻²⁹

Testing Procedure

The investigator performing the OMT technique had over five years of experience in routinely using the mobilization procedure. Each specimen was tested under each condition, where the order of conditions was randomly assigned, first by position then by load intensity. Distance from the reference ruler to each

marker was measured and recorded. Once positioned, a glide mobilization force was manually applied to the anterior tibia at the tibial tubercle in a posterior direction relative to the femur and parallel to the tibial plateau. The 44.48, 88.96, or 177.93 N force was measured by a hand-held dynamometer (MICROFET2, Hoggan Health Industries, Inc., Medical Products Division, Draper, UT) through the mobilization hand. A digital image was captured in an unloaded state (pre-load). The glide force was then applied and held for 60 seconds. A second digital image was captured at the end of the 60-second glide force while the load was sustained (post-load; Figure 2). This was repeated three times for each condition with a 60-second rest period between glide mobilization forces. Specimen # 2 and specimen # 8 were tested twice due to poor focus of the images. This second testing was not performed consecutively in relation to the first testing, where the order of conditions was again randomized.

At the end of testing, each specimen was dissected to ensure the meniscus marker was located in the anterior horn of the medial meniscus and to examine any meniscal abnormalities. In all eight specimens, the meniscus marker was correctly positioned and there were no observable meniscal abnormalities.

Data Reduction

The digital images were uploaded into a custom MATLAB analysis program (v.7.11.0, R2010b, The Mathworks, Inc., Natick, MA), where a single examiner manually digitized the marker coordinates. First, a 10-20 cm section of the aforementioned standard ruler was used within MATLAB data processing to calibrate subsequent measures. The raw data were used to determine marker position changes and displacement changes. The two tibial markers represented the reference line (tibial axis) for meniscal and femoral x and y coordinates. The perpendicular distance between the meniscal marker and the tibial axis represented meniscal marker positions. The perpendicular distance between the femoral marker and the tibial axis represented femoral marker position. The difference between the meniscal marker and femoral marker positions represented the meniscus – femoral marker position.

The following formulated process was used to establish each marker position:

1. The slope-intercept form ($y = mx + b$) of the line defined by the two markers on the tibia was established.
2. A point not on the line (e.g. meniscus marker) and a slope perpendicular to the tibia was used to calculate the slope-intercept form of the perpendicular line.
3. The two line-equations were solved simultaneously to calculate the coordinate of the point where they intersect.

Using this process, the marker position computation for each marker was conducted by calculating the perpendicular distance (r) of the marker (e.g. meniscus marker) from the point not on the line to the point where the lines intersect. The formula for calculating the perpendicular distance was represented by:

$$r = \sqrt{[(X^2 - X^1)^2 + (Y^2 - Y^1)^2]}$$

Where x and y are the coordinates of the two points.

Marker displacement was represented by changes in marker position in response to applied loads (Figure 3). For marker displacement (meniscal, femoral, or meniscal-femoral) at 0 deg knee flexion, the following formula was used to quantify the displacement:

$$\text{Marker Displacement} = \text{Marker position (0 deg X N)} - \text{Marker position (0 deg 0 N)}$$

Where $X = 44.48, 88.96$ or 177.93 N.

For marker displacement (meniscal, femoral, or meniscal-femoral) at 25 deg knee flexion, the following formula was used to quantify the displacement:

$$\text{Marker Displacement} = \text{Marker position (25 deg X N)} - \text{Marker position (25 deg 0 N)}$$

Where $X = 44.48, 88.96$ or 177.93 N

Statistical Analysis

Descriptive and inferential statistical analyses were conducted using the SPSS (v.18.0 for Mac 10.6x; IBM Corp, Armonk NY, USA) software. Tests for data normality were conducted using the Shapiro-Wilk Test. Alpha level was set at 0.05 for significance throughout all tests.

Figure 3. X-Y graph representing marker position change for unloaded and loaded conditions. The grey line represents 0 N (unloaded condition) and the black line represents 177.93 N (loaded condition).

Through the statistical analysis, the investigators first determined if the markers moved from a starting position to an end position (marker displacement) under a posterior tibial load. Mean and standard deviation (SD) values were calculated for changes in position for each marker. All data met the criteria for normality except femur position at 0 deg 88.96 N, as well as 0 deg 177.93 N. A non-parametric, Wilcoxon Signed Ranks Test was utilized for analyzing these data. Otherwise, separate 2-tailed dependent *t*-tests were used to analyze marker position differences in unloaded (0 N) versus loaded conditions (44.48, 88.96 or 177.93 N) at both knee angles. These tests were conducted for changes in: (1) meniscal marker position relative to tibial axis (representing a meniscotibial interface response); (2) femur marker position relative to tibial axis (representing a tibiofemoral interface response); and (3) meniscus minus femur marker position (representing a meniscomfemoral interface response).

Secondly, through the statistical analysis the investigators assessed for differences in the extent of marker

displacement across conditions. A separate 2 (knee position angle) x 3 (load intensity) repeated measures analysis of variance (ANOVA) was used to assess differences across conditions in: (1) meniscal marker displacement relative to tibial axis; (2) femoral marker displacement relative to tibial axis; and (3) meniscal marker displacement relative to femoral marker. Pair-wise post-hoc comparisons were performed to assess for location of significant differences.

Third, through the statistical analysis the investigators tested for differences in tibial angle across conditions. Tibial angle data were analyzed using a 2 (knee position angle) x 3 (load intensity) repeated measures ANOVA to determine if any angular change occurred between the femur and the tibia during the different conditions. Pairwise post-hoc comparisons were performed to assess for location of significant differences.

RESULTS

Specimen

A total of eight unembalmed frozen cadaveric knee specimens were considered and retained, with no

cadavers being excluded from the study in response to the exclusion criteria.

Digital images

A total of 36 images were captured per specimen, based on three trials each for two loading conditions (pre-load vs. post-load) at three load intensities (44.48 N vs. 88.96 N vs. 177.93 N) in two knee positions (0 deg vs. 25 deg). Overall, 288 images were analyzed via MATLAB as previously described.

Meniscal Marker Displacement

At both knee positions, all load x position conditions produced anterior displacement of the meniscal marker relative to the tibial axis (Table 1). The results of the paired samples t-tests for meniscus displacement relative to the tibial axis found that only the condition 3 pre-load – post-load computation (0 deg 0 N – 0 deg 177.93 N) demonstrated a

significant anterior meniscal marker displacement [$t(7) = -3.299$; $p = 0.013$] (Table 2). Therefore, the hypothesis of significant movement of the MMAH relative to the tibia was only supported under condition 3 (0 deg 177.93 N).

The results of 2 (knee position angle) x 3 (load intensity) ANOVA for meniscal marker displacement produced no significant position x load interaction [$F(2,14) = 0.307$, $p = 0.741$], nor significant main effects for load [$F(2,14) = 2.542$, $p = 0.114$] or position [$F(1,7) = 0.324$, $p = 0.587$], suggesting that any one combination of position and load were not superior for influencing the extent of meniscal marker displacement in this comparison.

Femoral Marker Displacement

The femoral marker demonstrated significant displacement in an anterior direction relative to the

Table 1. Descriptive data for meniscus and femur marker position and displacement. 1 = Meniscus and femur position and displacement relative to the tibial axis. 2 = Meniscus on femur refers to meniscus marker position and displacement relative to the femoral marker N = Newton, deg = Degree, STD = Standard Deviation, Displ = Displacement, Pos = Position, mm = millimeters.

Condition	Knee Position (deg)	Displacement Force (N)	Meniscus on Tibia 1			Tibia on Femur 1			Meniscus on Femur 2		
			Mean (mm)	STD	95%CI	Mean (mm)	STD	95%CI	Mean (mm)	STD	95%CI
1	0	0# Pos	2.6	4.5	-0.52, 5.72	4.57	16.27	-6.71, 15.85	-1.96	13.51	-11.32, 7.4
		44.48# Pos	2.67	4.46	-0.42, 5.76	6.87	16.47	-4.54, 18.28	-4.20	13.46	-13.52, 5.12
		44.48# Displ	0.06	0.29	-0.14, 0.26	2.3	1.75	1.09, 3.51	-2.24	1.73	-3.44, -1.04
2	0	0# Pos	2.54	4.51	-0.59, 5.74	5.7	16.19	-5.52, 16.92	-3.16	12.99	-12.16, 5.84
		88.96# Pos	2.8	4.25	-0.14, 5.74	9.28	16.29	-2.01, 20.57	-6.48	13.2	-15.62, 2.66
		88.96# Displ	0.26	0.48	-0.07, 0.59	3.58	1.66	2.43, 4.73	-3.32	1.45	-4.32, -2.32
3	0	0# Pos	2.47	4.46	-0.62, 5.56	4.45	16.65	-7.09, 15.99	-1.97	13.63	-11.42, 7.48
		177.93# Pos	2.88	4.3	-0.10, 5.86	10.61	16.67	-0.94, 22.16	-7.73	13.58	-17.14, 1.68
		177.93# Displ	0.41	0.35	0.17, 0.65	6.17	2.49	4.44, 7.9	-5.76	2.41	-6.96, -4.09
4	25	0# Pos	2.15	4.82	-1.19, 5.49	-2.00	14.49	-12.04, 8.04	4.16	11.5	-3.81, 12.13
		44.48# Pos	2.43	4.69	-0.82, 5.68	0.26	14.79	-9.99, 10.51	2.18	11.83	-6.02, 10.38
		44.48# Displ	0.28	0.38	0.02, 0.54	2.26	0.82	1.69, 2.83	-1.98	0.72	-2.48, -1.48
5	25	0# Pos	2.3	4.7	-0.96, 5.56	-1.50	16.25	-12.76, 9.76	3.8	13.67	-5.68, 13.28
		88.96# Pos	2.64	4.34	-0.37, 5.56	2.25	16.16	-8.95, 13.45	0.39	13.59	-9.02, 9.8
		88.96# Displ	0.34	0.65	-0.11, 0.79	3.75	2.75	1.85, 2.83	-3.41	2.39	-5.07, -1.75
6	25	0# Pos	2.25	4.74	-1.04, 5.54	-1.30	13.2	-10.44, 7.84	3.55	10.91	-4.01, 11.11
		177.93# Pos	2.79	4.2	-0.12, 5.70	5.78	13.85	-3.82, 15.38	-2.99	11.74	-11.12, 5.14
		177.93# Displ	0.54	0.73	0.03, 1.05	7.08	2.84	5.11, 9.05	-6.54	2.69	-8.4, -4.68

Table 2. Dependent t-tests for meniscus displacement relative to the tibial axis. 1 = Meniscal Marker Displacement with respect to the tibial axis. 2 = Femoral Marker Displacement with respect to tibial axis. 3 = Mensical minus Femoral Marker Displacement with respect to tibial axis. *sig (2-tailed) at $p = 0.05$. N = Newton, deg = Degree.

Condition	Load	Meniscus on Tibia 1			Tibia on Femur 2			Meniscus on Femur 3		
		t	df	Signif*	t	df	Signif*	t	df	Signif*
1	0deg 0N-0deg 44.48N	-0.619	7	.555	-3.716	7	.007*	3.658	7	.008*
2	0deg 0N-0deg 88.96N	-1.533	7	.169	-6.100	7	< .001*	6.492	7	< .001*
3	0deg 0N-0deg 177.93N	-3.299	7	.013*	-6.994	7	< .001*	6.756	7	< .001*
4	0deg 0N-25deg 44.48N	-2.166	7	.072	-7.749	7	< .001*	7.734	7	< .001*
5	0deg 0N-25deg 88.96N	-1.477	7	.183	-3.866	7	.006*	4.027	7	.005*
6	0deg 0N-25deg 177.93N	-2.084	7	.076	-7.047	7	< .001*	6.739	7	< .001*

Figure 4. Mean Marker Displacement across all conditions where the femoral marker (Fem Displ) and meniscal-femoral marker (Men-Fem Displ) represents mean displacement (and 95% CI) with respect to the tibial shaft, in mm. The tibial angle displacement (Tib Angle Displ) is represented in degrees.

tibial axis during all conditions in response to the posterior tibial mobilization (Table 1, Table 2, Figure 4). This supports the hypothesis of significant tibial displacement in relationship to the femur during this mobilization. The 2 (knee position angle) x 3 (load intensity) ANOVA produced no significant position x load interaction [$F(2,14) = 0.720$; $p = 0.504$] nor a significant main effect for position [$F(1,7) = 1.429$; $p = 0.271$]. However, a significant main effect for load [$F(2,14) = 77.994$; $p < 0.001$] was found. Post-hoc

pairwise comparison findings suggest that femoral marker displacement significantly increased with each increase in load, irrespective of knee position angle (Table 3). The 177.93 N load produced a significantly greater femoral marker displacement versus the 88.96 N ($p < 0.001$) and 44.48 N ($p < 0.001$) loads. Moreover, the 88.96 N load produced a significantly greater femoral marker displacement versus the 44.48 N ($p = 0.03$) load.

Meniscal-Femoral Marker Displacement

The meniscal-femoral marker displacement represented the displacement of the meniscal marker with respect to the femoral marker. There was a significant posterior movement of the meniscal marker with respect to the femoral marker (Table 1, Table 2, Figure 4). This does not support the hypothesis of insignificant movement of the MMAH relative to the femur. The 2 (knee position angle) x 3 (load intensity) ANOVA produced no significant position x load interaction [$F(2,14) = 1.192$; $p = 0.333$] nor a significant main effect for position [$F(1,7) = 1.042$; $p = 0.341$]. However, a significant main effect for load [$F(2,14) = 83.620$; $p < 0.001$] was found. Post-hoc pairwise comparison findings suggest that the meniscal-femoral marker displacement significantly increased with each increased load, irrespective of knee position angle across the majority of conditions (Table 3). Moreover, the 177.93 N load produced a significantly

Table 3. Post-hoc pairwise comparisons for femoral marker displacements with respect to tibia and meniscus. 1 = Femoral Marker Displacement with respect to tibial axis. 2 = Mensical minus Femoral Marker Displacement with respect to tibial axis .
*sig (2-tailed) at $p = 0.05$

Post Hoc Pairwise Comparisons										
Tibia on Femur 1					Meniscus on Femur 2					
Condition (I)	Condition (J)	Mean Difference (I-J)	Std. Error	Signif*	95% Confidence Interval for Difference		Std. Error	Signif*	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound			Lower Bound	Upper Bound
1	2	-1.34	0.42	.23	-3.16	0.49	0.30	.12	-0.20	2.40
	3	-4.14*	0.44	< .001*	-6.06	-2.22	0.40	< .001*	2.02	5.52
	4	0.12	0.59	1.00	-2.44	2.67	0.53	1.00	-2.58	2.00
	5	-1.59	0.64	.62	-4.35	1.18	0.51	.51	-0.88	3.57
	6	-5.30*	0.80	.01*	-8.80	-1.80	0.72	< .001*	1.76	8.04
2	3	-2.80*	0.48	.01*	-4.90	-0.71	0.44	0.01*	0.77	4.56
	4	1.45	0.38	.10	-0.22	3.13	0.37	.10	-2.98	0.20
	5	-0.25	0.52	1.00	-2.53	2.03	0.45	1.00	-1.72	2.20
	6	-3.97*	0.67	.01*	-6.89	-1.04	0.66	.01*	0.92	6.68
3	4	4.26*	0.71	.01*	1.18	7.33	0.71	.01*	-7.16	-0.95
	5	2.55*	0.40	.01*	0.80	4.30	0.31	< .001*	-3.76	-1.08
	6	-1.17	0.99	1.00	-5.48	3.15	0.88	1.00	-2.68	4.95
4	5	-1.71	0.80	1.00	-5.20	1.79	0.72	.85	-1.48	4.75
	6	-5.42*	0.80	< .001*	-8.91	-1.93	0.74	< .001*	1.96	8.42
5	6	-3.71	0.92	.07	-7.71	0.28	0.74	.03*	0.32	6.79

greater meniscal-femoral marker displacement versus the 88.96 N ($p < .001$) and 44.48 N ($p < 0.001$) loads.

Tibial Angle

Under each applied load, the tibial angle significantly moved into more knee extension (mean = -2.07 degrees, SD = 0.33) (Figure 4). The 2 (knee position angle) x 3 (load intensity) repeated measures ANOVA produced a significant main effect for tibial angle [$F(5,35) = 17.83$, $p < 0.001$]. The pairwise comparisons showed significant angular displacement of the tibia into extension, when the load intensity was greater regardless of the position of the knee (Table 4). Although non-significant, the other pairwise comparisons demonstrated the same trend of greater movement with greater force regardless of position of the knee. When the load intensity was equal, greater angular displacement occurred at 25 deg versus 0 deg knee position angle, except for a load intensity of 44.48 N.

Table 4. Post-hoc pairwise comparisons for tibial angular displacement. *sig at $p = 0.01$; Based on estimated marginal means using Bonferroni adjustment.

Condition (I)	Condition (J)	Mean Difference (I-J)	Std. Error	Signif*	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
1	2	0.55	0.22	.64	-0.42	1.52
	3	2.17*	0.37	.01*	0.57	3.77
	4	-0.26	0.32	1.00	-1.66	1.14
	5	1.30	0.54	.7	-1.04	3.63
	6	2.66*	0.34	< .001*	1.17	4.16
2	3	1.62*	0.28	.01*	0.42	2.81
	4	-0.81	0.17	.03*	-1.56	-0.06
	5	0.74	0.42	1.00	-1.09	2.58
	6	2.11*	0.30	< .001*	0.80	3.43
3	4	-2.43*	0.30	< .001*	-3.73	-1.13
	5	-0.87	0.40	.97	-2.61	0.86
	6	0.50	0.47	1.00	-1.55	2.54
4	5	1.56	0.53	.33	-0.76	3.87
	6	2.93*	0.37	< .001*	1.30	4.55
5	6	1.37	0.63	.98	-1.36	4.10

DISCUSSION

Anterior knee pain provoked during end-range passive knee extension may be related to a meniscal movement restriction and increased meniscal load during function. One method of treatment involves the use of manual posterior mobilization of the tibia to specifically target the meniscotibial interface of the knee joint. The results of the current study demonstrated significant meniscus marker displacement relative to the tibial axis during posterior tibial mobilization occurred at a position of 0 deg and under a force of 177.93 N. This finding suggests that posterior tibial mobilization may only be effective in moving the meniscus on the tibia at end-range of knee extension, where maximum congruency of the joint is achieved.¹⁴ Moreover, while such an in situ experiment cannot account for the role of pain or reactive muscular contraction during meniscotibial mobilization execution, the findings suggest that a substantial force may be required to achieve significant meniscotibial movement, encouraging clinicians to be less timid with mobilization forces during this specific application. This required force may be related to the amount of movement allowed between the meniscus and femur that is supported by these findings. Had the meniscus not moved on the femur during the technique in response to congruency between femoral condyle and meniscus, less force may have been required to create the same movement between meniscus and tibia as observed in this study. Thus, it appears that a modest amount of movement was allowed between the meniscus and femur, where the third hypothesis could not be supported. Yet, the femur appeared to serve as a buttress that limited further accompaniment of the meniscus with the tibia as the tibia was pushed posteriorly. Increased force was required to create the anterior meniscal displacement on the tibia, and primarily occurred in the fully extended position.

The findings of the present study support the use of posterior tibial glide mobilization to produce meniscal movement. Although the menisci do not move extensively, due to their anchors at the anterior horn and periphery, such meniscal motion is important for normal knee function. During in vivo studies, investigators observed that both menisci translate anteriorly with knee extension, where the anterior

horns move more than the posterior horns.^{17,30-32} Selected authors examined meniscal movement in vivo in healthy volunteers using MRI.^{30,32} Vedi et al³² found that the MMAH moved 0.54 cm and the posterior horn 0.38 cm while the lateral meniscus anterior horn moved 0.63 cm and the posterior horn 0.40 cm during unloaded knee motion from 90° flexion to full extension. Kawahara et al³⁰ examined meniscal movement during unloaded knee flexion. They report a posterior movement of the MMAH of 0.88 cm and posterior horn of 0.56 cm from 0° of flexion to 45° of flexion. From 45° of flexion to 90° of flexion the MMAH moved 1.16 cm and the posterior horn 0.64 cm in posterior direction.

When comparing such in vivo meniscal movement to the present paper's in situ movement, explored differences appear to be rather large. However, one should keep in mind that the reported in vivo values reflect meniscus movement throughout the entire rotatory flexion-to-extension range from 0° to 90° flexion while the present data reflects MMAH movement during a translatory passive tibial translation while the femur remains stationary. Thus, it is not surprising that MMAH movement during such passive posterior tibial mobilization technique in 0 degrees flexion with a mobilization force of 177.93N applied from the clinician did not result in a comparable movement range versus in vivo. This suggests that a better alternative for examining meniscal response to tibial mobilization should be conducted in vivo. However, cadaveric studies can provide valuable preliminary information to generate legitimacy for subsequent clinical trials. Accordingly, it was this paper's intent to gain a first insight into the feasibility of meniscal mobilization using an orthopedic manual therapy technique designed to encourage meniscal movement in the meniscotibial interface. Furthermore, the present study aimed to substantiate the existing internal evidence regarding the meniscal mobilization construct by establishing preliminary data. Therefore, inferences about whether 0.41mm MMAH movement is clinically meaningful for patients with MMAH impingement cannot be drawn from this study, thus inspiring future evaluations to address this question.

The authors of this study chose to test the joint in both 0 degrees and 25 degrees of flexion so to assess

the meniscal behaviors both within and outside of the knee's screw home mechanism^{17,18} and found that the meniscotibial response to posterior tibial mobilization was more profound at the 0-degree position where the joint is more congruent. In light of multiple soft tissue attachments to bone, the menisci dynamically guide and constrain joint motion throughout the available range.^{17,31} This function works with joint architecture to create joint congruency, stability, cartilage protection, and meniscal self-preservation.^{20,33} Medial-lateral joint surface asymmetry further constrains the movement toward the end of knee extension, where the screw-home mechanism creates greater joint congruency and forces lateral tibial rotation.^{17,18} These architectural features collaborate with the cruciate ligaments to influence anterior meniscal movement and contribute to constraining further extension.^{18,19,34} Thus, the present findings were no surprise, considering the change in joint congruency during end-range knee extension.

The current study's findings suggest that posterior tibial mobilization could influence MMAH translation on the tibia. Meniscal movement limits can emerge in response to inflammation and subsequent adhesive responses.¹⁵ As the knee approaches full extension, restrictions of meniscal movement may block the normal joint arthrokinematics.¹⁵ This movement constraint may lead to MMAH compression, resulting in knee extension limits and possible atypical anterior knee pain.¹² Additionally, meniscal injury can change knee movement mechanics and loading patterns, thus stressing articular cartilage.³⁵⁻³⁸ Such changes can lead to further meniscal problems. Investigators have observed significant changes in the anterior posterior meniscal movements related to architectural abnormalities that accompany knee joint pathology.^{30,39} Using a posterior tibial mobilization in terminal extension may be important for restoring appropriate movement of the meniscus on the femur (menisiofemoral interface) and tibia (meniscotibial interface).

Orthopedic manual therapy can be used to restore motion to a hypomobile joint.^{15,21} Mobilizations that stretch the soft tissues in a resting position or at the point of restriction (Grade III – IV mobilization) can be used to restore tibiofemoral, meniscotibial, and menisiofemoral arthrokinematics to gain optimal

joint motion, restore appropriate loading patterns, and achieve the highest level of function.^{14,21} In order to achieve a movement response in the meniscotibial interface, the present findings suggest that a substantial force (177.93 N) may be necessary to create the desired meniscotibial movement response in terminal extension. As a result, clinicians may be less timid with this specific technique and incorporate an appreciable force during posterior tibial mobilization in a knee with an intact posterior cruciate ligament, while continuing to respect a patient's pain response.

One could argue that a lack of significant meniscotibial displacement in conditions other than 0 deg and 177.93 N in the current study could be related to other architectural constraints in the knee that would limit total knee motion. However, one would then expect similar patterns in the results of menisiofemoral and or tibiofemoral displacements during the different conditions of the mobilization. The results show that this was not the case. First, the femoral marker significantly changed position relative to the tibial marker during all conditions, representing a significant tibial displacement relative to the femur. Moreover, the positive displacement values indicate the femur remained anterior to the tibial axis during a posterior load to the tibia. Because this is the first study to the authors' knowledge that examined meniscal movement on tibia during tibial mobilization, future research should examine the same phenomena in vivo to further elucidate this conjecture. Moreover, similar in vivo experimentation should examine clinical effects on those patients suspected of experiencing anterior knee pain related to anterior meniscal involvement in the condition.

The meniscal-femoral marker displacement differences were significant between the meniscus and the femur. Pairwise comparisons on the meniscal-femoral marker displacement ANOVA indicate more displacement at a greater load regardless of the position of the knee. This may be influenced by the fact that the femur displacement relative to the tibia was significant and the displacement of the meniscus relative to the tibia was essentially non-significant. This further suggests that the relative immobility of the meniscotibial interface resulted in the meniscus displacing with the tibia on the femur when the mobilizing force was applied.

The tibial angular movement, although small, was statistically significant suggesting that the movement produced during the current load x position conditions was not purely translatory, but under the applied loads the tibia moved into more extension. The authors decided to standardize and control the knee pre-position using the previously described rod through the tibia. Although a small amount of angular extension movement occurred in the tibia during posterior tibial mobilization, this configuration appears to support the anterior meniscal translation. Future research should examine the same parameters while allowing the distal tibia to translate in the same direction as the proximal region during the mobilization.

LIMITATIONS AND FUTURE RESEARCH

There are potential limitations of this study. The use of unembalmed cadaveric specimens, dissection, and subsequent mechanical fixation may not represent full in vivo response to posterior tibial mobilization. However, despite the mechanical fixation, significant movement in the tibiofemoral interface occurred, suggesting that sufficient movement did occur at the joint level. While cadaveric tissues do not fully represent living tissue dynamics with all the dynamic constraints that could accompany that use, the study introduces the potential meniscal movement that responds to a current OMT strategy. Future in vivo experimentation will provide further understanding of meniscal response to mobilization forces.

Specimen preparation included cutaneous and subcutaneous tissue removal, which may have changed the meniscal movement parameters of the specimens. However, all perceived important passive constraints were left intact, including the joint capsule, ligaments and retinacula. Considering the capsule's connection to the meniscus, one can be confident that meniscal movement parameters did not appreciably change. Future in vivo research will examine these test conditions with cutaneous and subcutaneous tissues intact, further addressing this concern.

The power level for the meniscal position t-test non-significant findings ranged from 11% to 73%. The lowest power test of 11% would have required 84 specimens to achieve a power of 80%. Although more specimens may have increased the power of

selected tests, the number of specimens needed to achieve 80% power for all tests was prohibitive for a cadaveric study.

This paper does not examine the role of the present mobilization on managing patients with anterior knee pain provoked with end-range passive knee extension. Orthopedic manual therapy techniques are commonly used to address knee pain and limitations.^{40,41} Authors propose using OMT to address meniscal movement in the meniscotibial and/or meniscomfemoral knee joint compartments.^{3,13,16} However, no evidence has yet to report the effects of these strategies on managing anterior knee pain provoked by end-range passive knee extension. The effect of such mobilization on cadaveric meniscal movement is a prerequisite to understanding the link between OMT to the meniscus (as in our study) and pain relief in this population. Based on our discoveries, future in vivo study replication using MRI should follow. Once confirmed, then a clinical trial examining the effects of the presently described mobilization on anterior knee pain and meniscal movement during end-range passive knee extension should be carried out.

CONCLUSIONS

To the authors' knowledge, this is the first study to examine movement of specific structures during a manually applied joint mobilization to the tibia in cadaveric specimens. This method could be used for future studies to investigate tissue response to OMT. Investigation and corroboration for in vivo studies could include magnetic resonance imaging. The findings of this study suggest that posterior tibial mobilization in an end-range extension position using a substantial force may produce MMAH translation in an anterior direction with respect to the tibial plateau. This technique may be most applicable in patients presenting with localized anterior knee pain provoked during passive end-range knee joint extension.

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