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Magnetic resonance analysis of loaded meniscus deformation: a novel technique comparing participants with and without radiographic knee osteoarthritis

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Abstract

Purpose—To establish a novel method of quantifying meniscal deformation using loaded MRI. More specifically, the goals were to evaluate the (1) accuracy, (2) inter-rater reliability, (3) intra-rater reliability, and (4) scan-rescan reliability. The secondary purpose of this experiment was to evaluate group differences in meniscal deformation in participants with and without radiographic knee OA.

Material and Methods—Weight-bearing 3T MRIs of the knee in full extension and 30-degrees of flexion were processed to create 3D models of meniscal deformation. Accuracy was assessed using a custom-designed phantom. Twenty-one participants either with or without signs of OA were evaluated, and another six participants (14 knees, one subject was scanned twice) underwent repeated imaging to assess scan-rescan reproducibility. Intraclass correlation coefficient (ICC), root-mean squared error (RMSE), and root-mean-square percent coefficient-of-variation (RMS %CV) analyses were performed. Exploratory comparisons were made between those with and without OA to evaluate potential group differences.

Results—All variables were found to be accurate with RMSE ranging from 0.08 to 0.35 mm and 5.99 to 14.63 mm^2. Reproducibility of peak anterior-posterior meniscal deformation was excellent (ICC > 0.821; p<0.013) with RMS%CV for intra-rater ranging from 0.06 to 1.53% and 0.17 to 1.97%, inter-rater ranging from 0.10 to 7.20% and 3.95 to 18.53%, and scan-rescan reliability ranging from 1.531 to 7.890% and 4.894 to 9.142%, for distance and area metric respectively. Participants with OA were found to have significantly greater anterior horn movement of both the medial (p=0.039) and lateral meniscus (p=0.015), and smaller flexed medial meniscus outer area (p=0.048) when compared to controls.

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Conflict of Interest The authors declare that they have no conflict of interest.

Conclusion—MRI based variables of meniscus deformation were found to be valid in participants with and without OA. Significant differences were found between those with and without radiographic OA; further study is warranted.

Keywords

Reproducibility; 3 Tesla Magnetic Resonance Imaging; Meniscal movement; Weight-Bearing; OA; Accuracy

Introduction

Knee osteoarthritis (OA) is common, affecting approximately 27 million (15%) Americans in 2005, and is predicted to increase to more than 18% or about 60 million people affected by the year 2020 [1, 2]. Functional impairments and pain are associated with this debilitating and chronic condition [1], and the only definitive method of treating knee OA is total knee arthroplasty [3]. Most agree that altered mechanical joint loading of the tissues (i.e. articular cartilage, menisci, ligaments, and joint capsule) is involved [4]. However, little is known about how these tissues interact within diseased knees.

The menisci have received considerable attention in the literature with regard to OA disease progression [5–18]. Others have suggested that altered meniscal function may be related to, or even precede, osteoarthritic progression [11, 14]. Biomechanically, menisci function to disperse loading of the cartilage in the tibiofemoral joint by acting as shock absorbers [19–21]. Contact stress across the articular cartilage is reduced by the menisci, which creates increased tibiofemoral contact area by increasing congruency of the joint surfaces [19, 20]. Further, the menisci are thought to transmit between 40% and 70% of the load across the knee [21]. For this purpose, load transmission across the joint requires the menisci to move as the femur and tibia move, maintaining a hoop-tension, without extruding out of the joint space [18, 22–24]. However, previous studies on meniscal deformation were limited by one or all of the following: poor image resolution, no functional load, only examining healthy knees [15, 25–31]. Further, only three investigations [30, 32, 33] to date have examined the relationship between meniscus movement and articular cartilage defects (in an unloaded condition). While these three studies [30, 32, 33] found that increased radial extrusion was related to cartilage pathology, none examined meniscal deformation in 3D (the addition of anterior and posterior motion and their related meniscal areas) with common clinical endpoints (e.g. Whole Organ Magnetic Resonance Imaging Score (WORMS) and Kellgren-Lawrence (KL)). Mediolateral and anterior-posterior meniscal extrusion, likely leads to altered joint loading and articular cartilage breakdown. However, there have been no 3D quantitative MRI studies yet to examine how absolute inner and outer areas of the menisci, and distances, or relative meniscal deformation, the change in position from when the knee is extended to when it is flexed, relates to knee OA.

Therefore, the primary purpose of this manuscript was to establish a novel method of quantifying meniscal deformation using loaded MRI. More specifically, the goals were to evaluate the (1) accuracy, (2) inter-rater reliability, (3) intra-rater reliability, and (4) scan-rescan reliability. The secondary purpose of this experiment was to evaluate group differences in meniscal deformation in participants with and without radiographic knee OA.

MATERIALS AND METHODS

Phantom Experiment

The accuracy of the meniscal deformation segmentation and algorithms were tested using a phantom that was created out of a 96 well culture dish (Corning, Union City, CA) with known dimensions supplied from the manufacturer (Figure 1A). Wells were filled with a mixture of 225 bloom gelatin (Gelatin Innovations Inc., Schiller Park, IL) and copper-sulfate to appear bright (Figure 1B), and the rest of the dish was filled with 225 bloom gelatin to avoid field inhomogeneities. This phantom was designed with similar distance and area dimensions to those found *in vivo* for meniscal areas and deformation. A spoiled gradient recalled acquisition (SPGR) sequence (TR/TE: 7.7/3.2 ms, FOV: 120 mm, matrix: 256 × 256 × 70, NEX: 1, BW: 62.5 kHz, FA: 18°, slice thickness: 1.0 mm, pixel size 0.4688 mm) was obtained. Images were segmented three times, and the average metric value was used to assess accuracy at each of the three known distances or areas.

Distances and areas were evaluated with cross-sectional images of the phantom (Figure 1B), and compared to the known distances (Figure 1C). The phantom cells were segmented to assess these distances. Areas were evaluated by segmenting a box with a width matching the diameter of the well (Figure 1D). The areas were quantified by multiplying the length of the region of interest by the number of slices. The following areas were assessed for accuracy: 153.0, 207.0, 304.5, and 367.5 mm^2.

Intra-rater and Inter-rater Reliability Experiment

Participants were recruited from our institution's orthopaedic surgery clinics or through advertising within the community if they met the following inclusion criteria: ≥ 35 years of age and a body mass < 87 kg. Participants were screened by phone for inclusion and the following exclusion criteria: MRI safety contraindications (e.g. potential pregnancy, ferrous metallic implants), history of knee surgery, and joint disease other than OA (e.g. inflammatory, crystalline, or infectious). Upon meeting these criteria, participants were invited to have a posterior-anterior fixed flexion radiograph using the SynaFlexer device (Synarc, Newark, CA, USA). The radiographs were read for the presence and grade of OA on the KL grading system by a board certified radiologist. The knee selected of the participants with OA was the knee with the greater KL grade. For the OA group only those with a KL score of 2 were enrolled, and participants without radiographic knee OA had their knee selected for them with a random assignment. All procedures were explained and all participants signed informed consent that was approved prior to their inclusion in the study by the University's Committee on Human Research in accordance with the ethical standards in the 1964 Declaration of Helsinki.

Intra-rater reliability was assessed, based upon the recommendations of Glüer et al [34], with 3 repeated measurements per individual on a group of 14 individuals without radiographic evidence of knee OA (KL score of 0). Further, to assess the intra-rater reliability in knees with OA, 3 repeated measurements per individual were made on a group of 7 participants with radiographic evidence of knee OA (KL score of 2).

Inter-rater reliability was assessed across two raters on the same participants included in the intra-rater reliability experiment. The raters were blinded to the other's measurements, and during both the intra-rater and inter-rater reliability experiments the raters were blinded to the disease status of the individual.

Scan-Rescan Reliability Experiment

Additional participants from a prior bilateral knee imaging study were evaluated for scan-rescan reliability. Participants were recruited if they were between 15 and 55 years old, without any ligamentous or meniscal surgery, with no history of arthritis, full knee range of motion, and able to perform athletic tasks (i.e. running and jumping). Analysis was conducted on 14 knees (6 participants; one subject was scanned twice) that underwent the knee kinematic imaging protocol twice by a single rater. Participants were removed from the scanner and then repositioned within the scanner between each image collection, as was suggested to be best practice for assessment of short term scan-rescan reliability previously [34].

Loading and MRI Protocol

MR images were acquired with a 3T MR scanner (Signa 3T; GE Healthcare, Waukesha, WI) and an 8-channel phased array knee coil (Invivo, Orlando, FL). Participants were positioned supine on top of a custom-made MRI-compatible loading apparatus with the study knee in full knee extension, with padding under the pelvis and leg to ensure consistent comfortable knee positioning and to minimize movement. A load of 25% of the participants' body mass was applied as shown in Figure 2. First, the knee was imaged in full extension. Next, the knee was positioned in approximately 30 degrees of knee flexion (supported by the knee coil), with restraints and padding in place to reduce movement. The total time for image acquisition, including set up, was approximately 20 minutes. For both conditions, participants were scanned with a sagittal oblique non-fat saturated T_2-weighted Fast Spin Echo (FSE) sequence (TR/TE: 4300/51 ms, phase FOV: 200 mm, matrix: 384 × 192, slice thickness: 1.5 mm, pixel size 0.521 × 0.729 mm, Echo Train: 9, BW: 31.25 kHz).

Description of Meniscus Segmentation

The bodies and horns of the medial and lateral meniscus were manually segmented using Bezier-splines implemented with in house software developed in Matlab (MathWorks, Natick, MA; [35]). The meniscal body, anterior horn (AHN), and posterior horn (PHN) were segmented separately for the medial and lateral menisci (Figure 3). Segmentation began on the first slice the body was identified, and continued mesially until volume-averaging was present from the cruciate ligaments. Cruciate ligament volume-averaging was defined as visual detection of artifact from a cruciate ligament that interfered with meniscal horn segmentation. This volume-averaging landmark was chosen because it was an easily reproduced slice. The same process was used for both medial and lateral menisci.

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Meniscal Deformation Variables

Three relative (the change in position from flexion to extension) and 4 absolute variables (representative of both flexion and extension) were calculated for the medial and lateral menisci. The three relative variables were calculated by using an in-house 3D image registration program to align images based on tibial landmarks. This algorithm translated, rotated, and scaled the segmented tibiae to match corresponding anatomical landmarks by minimizing the least squared errors of the residual distances between these corresponding landmarks. This in-house program has been used previously by others [27, 36–38] to perform tibiofemoral kinematic studies. Once the tibiae were registered to each other peak anterior-posterior deformation of meniscal horns, and medial-lateral body deformation, from flexion to the position in extension were calculated for both the medial and lateral meniscus (Figure 4). Anterior horn distance represents the change in position of the peak anterior position in flexion minus the position in extension, posterior horn distance is the change in position from the peak posterior position, and body distance is the peak medial or lateral change for the medial or lateral meniscus, respectively. In addition, four absolute variables were quantified in both flexed and extended positions for both the medial and lateral meniscus: inner anterior horn to posterior horn (AHN-PHN) distance, outer AHN-PHN distance, inner area, and outer area (Figure 4). The inner AHN-PHN distance was measured on the most mesial slice segmented as the distance from the most posterior point of the anterior horn to the most anterior point on the posterior horn. The outer AHN-PHN distance was measured as the peak distance (across all slices that horns were segmented) between the most anterior point on the anterior horn to the most posterior point on the posterior horn. The inner area was quantified as the distance between the innermost points of the anterior and posterior horns multiplied by the number of slices that only horns were segmented. The outer area was defined as the distance between the outermost points of the horns and body multiplied by the number of slices segmented.

Reproducibility and Statistical Analyses

Accuracy was evaluated using root mean square error (RMSE). The amount of agreement of intra-rater, inter-rater, and scan-scan reliability was evaluated using an intraclass correlation coefficient (ICC; [39]). ICC values were operationally defined as having poor reproducibility if less than 0.40, within 0.40 to 0.75 as fair to good reproducibility, and greater than 0.75 as excellent reproducibility [40]. Further, absolute variables (inner AHN-PHN distance, outer AHN-PHN distance, inner area, and outer area) were assessed for reliability using root mean squared percent coefficient of variability (RMS%CV). Relative variables (anterior horn, body, and posterior horn deformation) were not assessed for reliability using RMS%CV as this test is not appropriate [41]. Finally, in an exploration study, non-paired one-tailed student's t-tests were used to test for potential differences between control participants and those with radiographic OA, with an alpha value of 0.05.

Results

Phantom Experiment: Accuracy

Distance and area RMSE ranged from 0.08 to 0.35 mm and 5.99 to 14.63 mm^2, respectively (Table 1). Distance error stayed fairly constant across the range of values tested, while area error decreased from 13.99 to 5.99 mm^2 as the area tested increased (Table 1).

Intra-rater Reproducibility

The 14 participants included in the control group included 6 males and 8 females aged 47.1 ± 10.4 years. The 7 participants with radiographic knee OA included 4 males and 3 females aged 55.6 ± 6.5 years.

ICCs were excellent across all dependent variables for both control participants and those with OA (Tables 2 and 3). RMS%CV ranged from 0.17% to 1.53% across the absolute variables with the lateral meniscus having higher values than the medial meniscus both in extension and flexion (Table 3).

Inter-rater Reproducibility

The demographics of the participant population of the inter-rater reliability experiment were the same as the intra-rater reproducibility experiment.

In general ICCs were found to be excellent (Tables 4 and 5). However, body mediolateral movement was found to have poor reproducibility between raters for the lateral meniscus and fair to good reproducibility (defined as an ICC > 0.40 and < 0.75) for OA participants in the medial meniscus (Table 4). RMS%CV for absolute values ranged from 0.10% to 18.53%, with the lateral meniscus having greater values than the medial meniscus in both flexion and extension (Table 5).

Scan-Rescan (Intra-rater) Reproducibility

Participants were comprised of 3 females and 3 males aged 26.6 ± 1.1 years. Excellent reliability was found for all variables (Tables 6 and 7), with the exception of body movement. Peak body medial-lateral deformation was found to have fair to good reproducibility, with values greater than 0.621 (Table 6). The medial and lateral meniscus had RMS%CV ranging from greater than 1.53% and less than 9.14% in both flexion and extension.

Meniscal Deformation Differences Between KL2 and KL0 Group

Preliminary results indicate that the anterior horn moved significantly farther in the knee OA group in comparison to the control group of both the medial (0.33 versus 1.53 mm, P = 0.039) and lateral meniscus (1.66 versus 3.67 mm, P = 0.015; Table 8). Further, the outer area of the flexed medial meniscus was smaller in the knee OA group in comparison to the control group (Table 9).

Discussion

The objectives of this study were to (1) determine the accuracy of a MRI-based algorithm used to quantify meniscus deformation between 30 degrees of knee flexion and full knee extension, and (2) report the intra-, inter-, and scan-rescan reliability of meniscal deformation. A secondary purpose was to determine if meniscal deformation differed between participants with and without radiographic OA. In general, these variables were found to have relatively small RMSE when metric accuracy was tested on a copper-sulfate phantom of known dimensions. In addition, meniscus deformation variables were found to be reliable within and between raters, and over a short-term scan-rescan testing time. Acceptable RMS%CV values were found for absolute variables across inter-rater, intra-rater, and scan-rescan experiments. Finally, some variables were found to be different between participants with and without radiographic knee OA.

In this study, all variables were found to be accurate by testing a phantom with known distances and areas, as distances were found to have residual RMSE values smaller than a pixel (0.4688 mm) and areas were smaller than 19 pixels (0. 4688 mm pixels over 1 mm slices). Further, RMSE residuals were less than 3% of the known value for areas greater 300 mm^2 (Table 1). Although, the phantom used does not represent all of the challenges of imaging and segmenting a meniscus, especially with using a different imaging sequence. However, the purpose of using a phantom was to evaluate the accuracy of the segmentation algorithm and variable calculations (as these were not trivial) on a model with known dimensions, and a separate sequence was used to optimize images of the phantoms without potential blur. Once these segmentations and algorithms were confirmed as accurate, we tested their reliability with the hope of validating our deformation variables in the menisci.

The reliability of meniscal deformation variables were evaluated on participants with and without knee OA at 3.0 T MRI while under a load of 25% of body weight. Raters were found to be reliable both within and between each other, and over a short time period in a scan-rescan experiment. In support of this ICCs were found to be excellent in all reliability studies, with the exception of the out-of-plane quantification of body movement when two raters were evaluating cases. Therefore, the medial-lateral movement may be more reliably evaluated using images acquired in the coronal plane when more than one rater is used. RMS%CV were smallest with only one rater, and in all cases less than 2%. With two raters, RMS%CV were more precise for the Inner and Outer AHN-PHN distances (less than 7.5% and 2%, respectively) than the Inner and Outer Areas (less than 19% and 11%, respectively). Further, these variables tended to be more precise for the medial meniscus than the lateral meniscus, in both flexion and extension (Table 5). Finally, scan-rescan RMS%CV values followed a similar trend to those of intra-rater precision, with distances being more precise than areas and medial meniscus more precise than lateral meniscus, however all were less than 8.5% (Table 7).

Previously reported studies on meniscal deformation did not always report absolute values, so comparisons to previous literature were challenging. For instance Kawahara et al. reported a meniscal ratio of length between 0 and 45 degrees, but did not report any absolute distances [30]. Further, Shefelbine et al. [27] reported meniscal positions as a percentage of the tibial anterior-posterior width. In what may be the most comparable study, von Eisenhart-Rothe et al. [26] examined the movement of the posterior horn of the medial and lateral meniscus between 30 and 90 degrees of knee flexion while participants contracted their knee extensors. In that study, both the ACL deficient and healthy control participants were found to have less than 2 mm of posterior movement of the posterior horns and those values are similar to those found within this study (Table 8). Another study done by Vedi et al. [29] examined healthy participants that were standing in an open MRI at 0.5 T at full knee extension and 90 degrees of knee flexion. This study found that in the anterior-posterior direction the lateral meniscus moved more than the medial, and the anterior horns move more than the posterior horns. All values found in the study done by Vedi et al. were greater than 3.6 mm, which represents much greater movement than found in the current study. However, the study done by Vedi et al. moved through a greater range of knee motion so larger meniscal movement would be expected.

To build on previous experiments, this study included new measurements of meniscal deformation and shape. Additional variables suggested for future use in this experiment, such as the inner and outer AHN-PHN distance, and inner and outer area, have not been quantified in the past so we are unable to make comparisons. However, among these novel variables may be a biomarker for knee OA progression that was not examined previously. For instance, the outer area of the medial meniscus in the flexed knee was significantly smaller on average for participants in the knee OA group ($p < 0.048$). A smaller outer medial meniscal area indicates that meniscal function is altered and may not be increasing the contact area across the tibiofemoral joint as is normally the case. These data may support previous hypotheses that altered meniscal function may precede knee OA [7, 8, 10–12, 14, 18]. Although previous studies have examined meniscal deformation across knee angles at ≤ 1.5 T MRI [19, 25–30], no studies were found examining 3D meniscal deformation in participants with knee OA while under physiologically relevant loads [5, 32]. Perhaps future studies with aims to characterize potential differences between groups would reveal more robust differences.

This study had several limitations. First, the scan parameters were not the same between the phantom and in vivo experiments. The phantom experiments were meant to evaluate the reproducibility segmentation and distance algorithms developed for this study, not assess the in vivo reproducibility, which was evaluated separately. Second, only sagittal oblique images were analyzed. While this is likely responsible for the high levels of reproducibility observed in peak anterior horn and posterior horn deformation, the medial-lateral body intra-rater reliability would likely improve with images acquired in the coronal plane. However, the primary purpose of this study was to describe 3D meniscal deformation and the sagittal oblique images would likely outperform coronal images for anterior and posterior horn deformation. Third, short-term but not long-term reliability was determined, therefore care should be taken when making within participant comparisons with a longer (months) time period between scans. Further, while the short-term scan-rescan reliability was excellent for sagittal plane deformation and meniscal areas, there were fewer than the recommended [34] number of subjects or repeated examinations suggesting care may needed to be taken when interpreting these scan-rescan results. Finally, the population age range was limited to older adults, and findings may not represent those of younger adults. In addition, group-differences were assessed on a relatively small cohort of participants grouped by two grades (KL 0 and 2). However, preliminary data suggest further study is warranted across a wider range of participants.

In conclusion, findings from this study suggest that sagittal plane meniscal deformation and areas are accurate, reliable within and between raters, and reliable across scans in the short term. Preliminary findings indicate that significant differences may exist between those with and without radiographic OA, however further study is needed. These findings suggest that investigating meniscal deformation while under load may be a valuable tool to improve our understanding on the evolution of OA.

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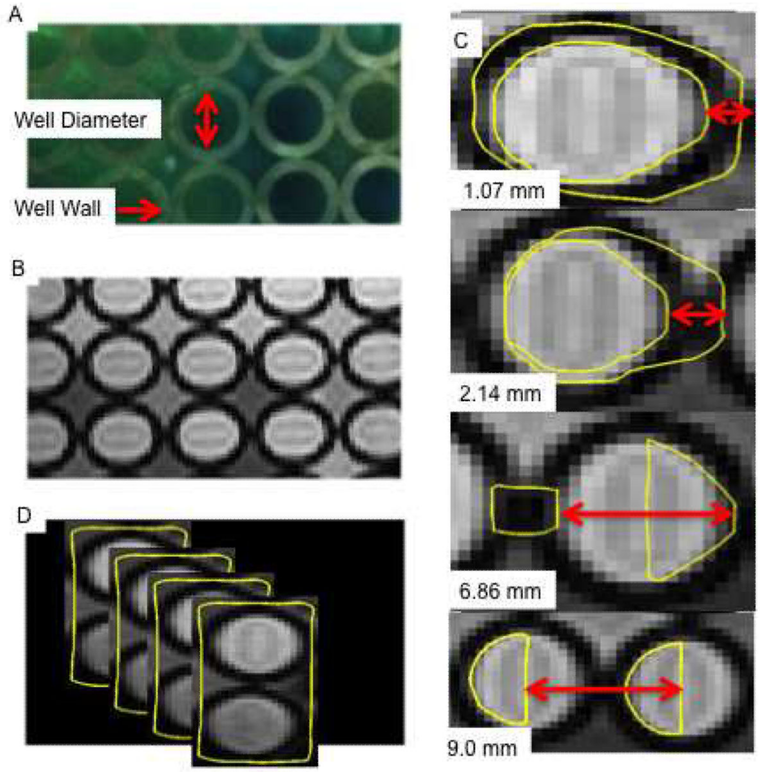
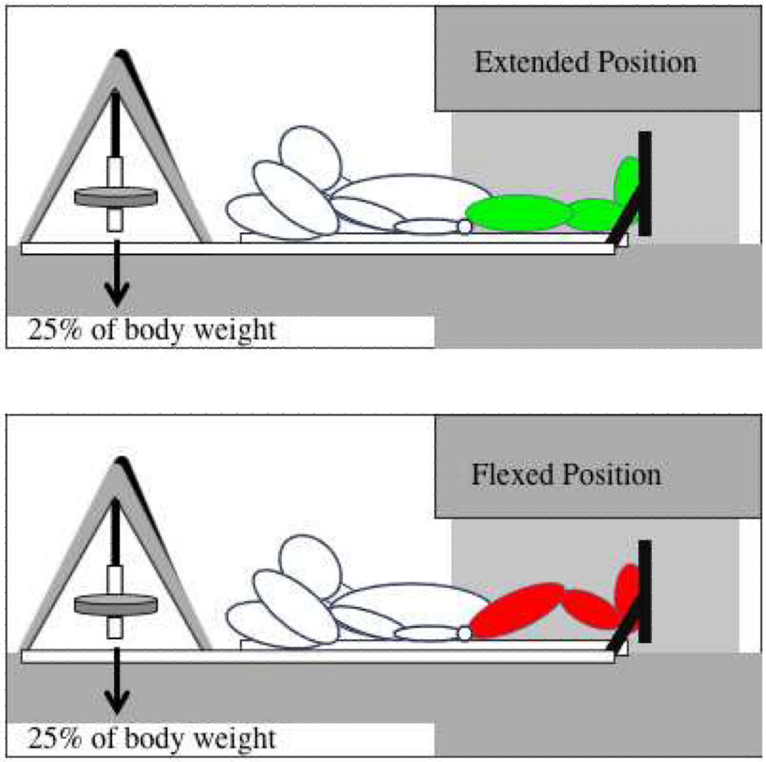


1. Phantom used to validate method (A) well plate, (B) MRI of well plate, (C) segmentations used to quantify known distances, (D) segmentations used to quantify coverage area of known areas. Variables were compared to the known distances: 1.07 mm, 2.14 mm, 6.86 mm, and 9 mm.



2. Loading device, custom made, for axial loading during MRI. Weights were hung behind the patient. Pulleys and the loading plate transmit the compressive force on the foot and load the knee joint.

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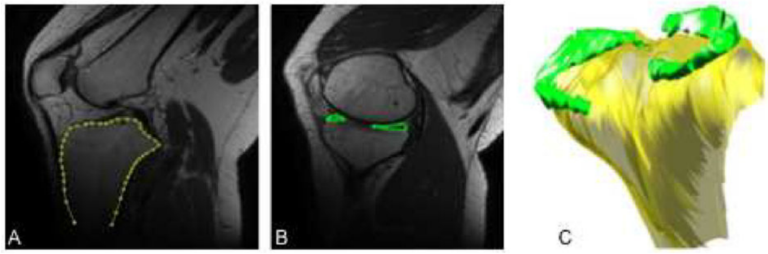
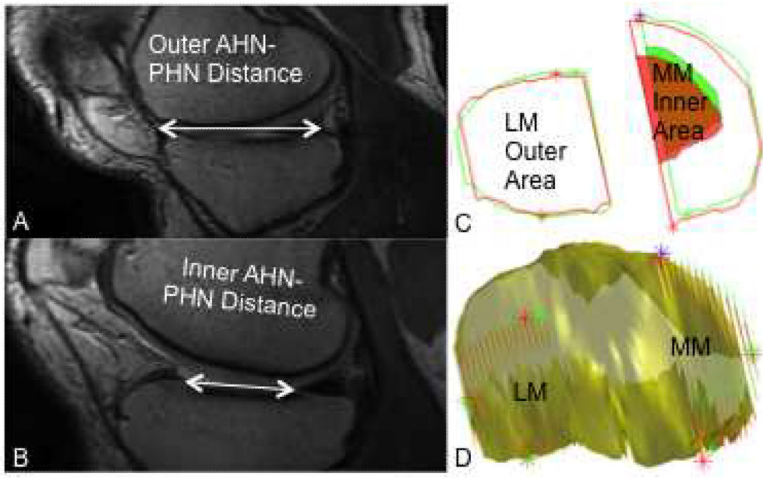


3. Figure outlining representative segmentations used to quantify meniscal deformation. The tibia was segmented (**a**) for use as a reference system, the meniscus (**b**), and figures were generated (**c**).



4. Variables used to evaluate meniscal deformation: outer AHN-PHN distance (a), inner AHN-PHN distance (b), outer area and inner area of lateral meniscus (LM) and medial meniscus (MM) respectively (c), and anterior horn, body, posterior horn peak distance indicated with astrices (d). Green indicates extended and red flexed positions (cd).

Table 1

Accuracy of experimentally quantified distance and area in comparison to known values.

Distance (mm)			Area (mm^2)		
Known	**Quantified**	**RMSE**	**Known**	**Quantified**	**RMSE**
1.07	1.09	0.08	153.00	165.98	13.99
2.14	2.16	0.15	207.00	220.07	14.63
6.86	6.59	0.35	304.50	312.64	9.28
9.00	9.00	0.15	367.50	373.07	5.99

Table 2

Intra-rater reliability for peak meniscal horn deformation of participants between extension and flexion.

	Anterior Horn			Body			Posterior Horn		
ROI	**Mean (mm)**	**ICC**	***p-value***	**Mean (mm)**	**ICC**	***p-value***	**Mean (mm)**	**ICC**	***p-value***
Medial Meniscus									
Control	0.437	0.995	*<0.001*	−0.120	0.987	*<0.001*	1.068	0.997	*<0.001*
OA	1.257	0.995	*<0.001*	−0.118	0.982	*<0.001*	1.334	0.999	*<0.001*
Group	0.711	0.995	*<0.001*	−0.119	0.985	*<0.001*	1.156	0.997	*<0.001*
Lateral Meniscus									
Control	1.655	0.997	*<0.001*	−1.009	0.992	*<0.001*	0.740	0.997	*<0.001*
OA	3.211	0.998	*<0.001*	−0.803	0.994	*<0.001*	1.537	0.999	*<0.001*
Group	2.173	0.998	*<0.001*	−0.940	0.993	*<0.001*	1.006	0.998	*<0.001*

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Table 3

Intra-rater reliability for peak meniscal distance and area of participants during extension and flexion.

Inner AHN-PHN Distance			Outer AHN-PHN Distance		Inner Area		Outer Area	
ROI	**Mean (mm)** ***RMS %CV***	**ICC** **p-value**	**Mean (mm)** ***RMS %CV***	**ICC** **p-value**	**Mean (mm^2)** ***RMS %CV***	**ICC** **p-value**	**Mean (mm^2)** ***RMS %CV***	**ICC** **p-value**
Medial Meniscus Extended								
Control	25.121 *0.58*	0.999 *<0.001*	45.551 *0.40*	0.999 *<0.001*	207.133 *0.70*	1.000 *<0.001*	700.991 *0.17*	1.000 *<0.001*
OA	27.345 *0.70*	0.998 *<0.001*	45.155 *0.39*	1.000 *<0.001*	260.909 *0.63*	1.000 *<0.001*	725.810 *0.30*	1.000 *<0.001*
Group	25.862 *0.63*	0.999 *<0.001*	45.419 *0.40*	0.999 *<0.001*	225.058 *0.67*	1.000 *<0.001*	709.264 *0.22*	1.000 *<0.001*
Lateral Meniscus Extended								
Control	14.910 *1.53*	0.998 *<0.001*	33.889 *0.41*	0.998 *<0.001*	220.426 *0.83*	0.999 *<0.001*	699.887 *0.35*	1.000 *<0.001*
OA	15.003 *0.94*	0.999 *<0.001*	35.431 *0.39*	0.999 *<0.001*	269.342 *1.87*	1.000 *<0.001*	769.714 *1.63*	0.998 *<0.001*
Group	14.941 *1.36*	0.998 *<0.001*	34.403 *0.40*	0.999 *<0.001*	236.732 *1.38*	0.999 *<0.001*	723.163 *1.04*	0.999 *<0.001*
Medial Meniscus Flexed								
Control	25.368 *0.08*	0.999 *<0.001*	46.182 *0.12*	0.999 *<0.001*	252.282 *0.97*	1.000 *<0.001*	774.153 *1.97*	0.999 *<0.001*
OA	27.132 *0.07*	1.000 *<0.001*	45.232 *0.10*	1.000 *<0.001*	275.744 *0.48*	1.000 *<0.001*	734.994 *0.91*	1.000 *<0.001*
Group	25.956 *0.07*	0.999 *<0.001*	45.865 *0.12*	0.999 *<0.001*	260.103 *0.80*	1.000 *<0.001*	761.100 *1.62*	1.000 *<0.001*
Lateral Meniscus Flexed								
Control	14.217 *0.09*	0.998 *<0.001*	32.975 *0.09*	0.998 *<0.001*	190.510 *0.64*	1.000 *<0.001*	640.806 *1.25*	1.000 *<0.001*
OA	14.712 *0.09*	0.998 *<0.001*	33.757 *0.06*	1.000 *<0.001*	236.826 *0.70*	1.000 *<0.001*	729.352 *1.52*	1.000 *<0.001*
Group	14.382 *0.09*	0.999 *<0.001*	33.236 *0.08*	0.999 *<0.001*	205.949 *0.66*	1.000 *<0.001*	670.322 *1.34*	1.000 *<0.001*

Table 4

Inter-rater reliability for peak meniscal horn deformation of participants between extension and flexion.

	Anterior Horn			Body			Posterior Horn		
ROI	**Mean (mm)**	**ICC**	***p-value***	**Mean (mm)**	**ICC**	***p-value***	**Mean (mm)**	**ICC**	***p-value***
Medial Meniscus									
Control	0.503	0.928	<0.001	−0.346	0.784	0.005	0.970	0.976	<0.001
OA	1.314	0.904	0.006	−0.243	0.655	**0.110**	1.404	0.961	<0.001
Group	0.773	0.928	<0.001	−0.312	0.767	0.001	1.115	0.969	<0.001
Lateral Meniscus									
Control	1.607	0.984	<0.001	−1.004	−0.042	**0.529**	0.704	0.996	<0.001
OA	3.281	0.985	<0.001	−0.758	0.687	**0.092**	1.480	0.994	<0.001
Group	2.165	0.987	<0.001	−0.922	0.373	**0.152**	0.963	0.995	<0.001

Table 5

Inter-rater reliability for meniscal distance and area of participants during extension anc flexion.

	Inner AHN-PHN Distance		Outer AHN-PHN Distance		Inner Area		Outer Area	
ROI	**Mean (mm) RMS % CV**	**ICC p-value**	**Mean (mm) RMS % CV**	**ICC p-value**	**Mean (mm^2) RMS % CV**	**ICC p-value**	**Mean (mm^2) RMS % CV**	**ICC p-value**
Medial Meniscus Extended								
Control	25.302 0.41	0.883 <0.001	45.539 0.28	0.989 <.001	211.312 9.76	0.936 <0.001	700.765 5.52	0.924 <0.001
OA	27.212 0.10	0.997 <0.001	44.904 0.63	0.966 <0.001	257.532 9.97	0.933 0.002	711.472 7.90	0.928 0.003
Group	25.938 0.31	0.943 <0.001	45.328 0.40	0.977 <0.001	226.718 9.89	0.905 <0.001	704.334 6.43	0.923 <0.001
Lateral Meniscus Extended								
Control	15.120 6.73	0.926 <0.001	33.796 1.24	0.980 <0.001	206.510 16.15	0.886 <0.001	664.919 10.82	0.847 0.001
OA	15.677 7.20	0.954 0.001	35.402 1.00	0.994 <0.001	243.316 18.53	0.959 0.001	719.091 10.74	0.974 <0.001
Group	15.305 6.90	0.930 <0.001	34.331 1.16	0.988 <0.001	218.779 17.22	0.919 <0.001	682.977 10.80	0.907 <0.001
							Medial Meniscus Flexed	
Control	25.204 2.70	0.960 <0.001	46.007 1.60	0.982 <0.001	251.201 4.59	0.981 <0.001	760.670 3.95	0.981 <0.001
OA	27.157 0.99	0.996 <0.001	44.994 2.25	0.966 <0.001	283.244 6.23	0.986 <0.001	731.462 4.12	0.983 <0.001
Group	25.855 2.23	0.978 <0.001	45.669 1.84	0.977 <0.001	261.882 5.30	0.981 <0.001	750.934 4.01	0.981 <0.001
							Lateral Meniscus Flexed	
Control	14.408 3.34	0.967 <0.001	32.893 0.95	0.984 <0.001	182.962 7.99	0.982 <0.001	618.375 6.36	0.958 <0.001
OA	14.766 6.06	0.867 0.013	33.600 0.62	0.998 <0.001	220.270 16.38	0.935 0.002	692.563 9.82	0.926 0.003
Group	14.527 4.47	0.935 <0.001	33.129 0.85	0.992 <0.001	195.398 12.29	0.957 <0.001	643.104 7.88	0.945 <0.001

Table 6

Scan-rescan reliability of peak meniscal horn deformation of participants between extension and flexion.

	Anterior Horn			Body			Posterior Horn		
ROI	**Mean (mm)**	**ICC**	***p-value***	**Mean (mm)**	**ICC**	***p-value***	**Mean (mm)**	**ICC**	***p-value***
Medial Meniscus									
	1.758	0.847	0.001	−0.947	0.625	0.044	1.391	0.833	0.001
Lateral Meniscus									
	5.382	0.881	< 0.001	−0.168	0.621	0.046	3.724	0.821	0.002

Table 7

Scan-rescan reliability for meniscal distance and area of participants during extension and flexion.

	Inner AHN-PHN Distance		Outer AHN-PHN Distance		Inner Area		Outer Area	
	Mean (mm)	**ICC**	**Mean (mm)**	**ICC**	**Mean (mm^2)**	**ICC**	**Mean (mm^2)**	**ICC**
ROI	**RMS % CV**	**p-value**	**RMS % CV**	**p-value**	**RMS % CV**	**p-value**	**RMS % CV**	**p-value**
Medial Meniscus Extended								
	28.127	0.977	47.771	0.955	274.513	0.934	774.592	0.935
	2.449	<0.001	1.720	<0.001	9.142	<0.001	4.894	<0.001
Lateral Meniscus Extended								
	13.957	0.908	35.588	0.937	245.385	0.824	775.892	0.860
	7.890	<0.001	2.344	<0.001	7.955	0.002	6.252	0.001
Medial Meniscus Flexed								
	25.789	0.853	47.404	0.941	335.999	0.963	842.981	0.932
	7.245	0.001	2.313	<0.001	7.241	<0.001	5.735	<0.001
Lateral Meniscus Flexed								
	14.276	0.941	33.931	0.939	196.090	0.824	675.100	0.893
	5.324	<0.001	1.531	0.001	8.244	0.002	5.774	<0.001

Table 8

Mean meniscal deformation of control participants and osteoarthritic participants between extension and flexion.

	Anterior Horn		Body		Posterior Horn	
ROI	**Mean (mm)**	**p-value**	**Mean (mm)**	**p-value**	**Mean (mm)**	**p-value**
Medial Meniscus						
Control	0.33 ± 1.67	**0.039**	−0.18 ± 1.19	0.391	1.07 ± 1.88	0.244
OA	1.53 ± 1.39		−0.32 ± 1.39		1.61 ± 1.78	
Lateral Meniscus						
Control	1.66 ± 1.76	**0.015**	−1.08 ± 1.02	0.243	0.73 ± 1.51	0.104
OA	3.67 ± 2.5		−0.71 ± 1.56		1.71 ± 2.18	

Quantified mean ± standard deviation

Table 9

Mean meniscal distance and area of control participants and osteoarthritic participants during extension and flexion.

	Inner AHN-PHN Distance		Outer AHN-PHN		Inner Area		Outer Area	
ROI	**Mean (mm)**	**p-value**	**Mean (mm)**	**p-value**	**Mean (mm^2)**	**p-value**	**Mean (mm^2)**	**p-value**
Medial Meniscus Extended								
Control	25.07 ± 2.19	0.228	45.41 ± 3.11	0.283	206.79 ± 62.43	0.146	700.14 ± 122.74	0.142
OA	23.33 ± 8.27		44.37 ± 5.56		242.49 ± 99.97		615.2 ± 252.27	
Lateral Meniscus Extended								
Control	14.8 ± 2.74	0.357	33.86 ± 2.01	0.139	219.7 ± 67.29	0.090	699.33 ± 112.6	0.367
OA	14.33 ± 3.5		35.1 ± 3.42		262.61 ± 84.78		675.53 ± 223.48	
Medial Meniscus Flexed								
Control	25.35 ± 2.43	0.212	46.15 ± 3.63	0.191	252.01 ± 62.93	0.391	774.32 ± 125.02	**0.048**
OA	23.63 ± 7.4		44.45 ± 5.68		261.66 ± 106.57		636.8 ± 258.84	
Lateral Meniscus Flexed								
Control	14.27 ± 1.85	0.221	32.93 ± 1.77	0.422	190.33 ± 56.9	0.142	639.7 ± 92.69	0.432
OA	13.34 ± 3.9		33.14 ± 3.27		221.06 ± 80.61		628.14 ± 226.98	

Quantified mean ± standard deviation