MR IMAGING AND 3-D ARTICULAR CARTILAGE THICKNESS MAPPING OF A MECHANICALLY LOADED KNEE JOINT WITH AND WITHOUT MENISCECTOMY
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INTRODUCTION
High resolution imaging of an entire joint under physiologic load will allow one to determine articular cartilage deformation and will contribute to our understanding of the mechanical basis of osteoarthritis. Meniscectomy has been shown in the sheep and in humans to lead to osteoarthritis of the knee [1,2]. Previous studies have examined the effects of meniscectomy on the contact stress distribution of the knee [1,2], but three-dimensional mapping of the changes in articular cartilage deformation due to meniscectomy have never been measured. In this study, we hypothesize that an entire knee joint can be loaded to a physiologic level inside a high resolution 4.7T MRI scanner, and that entire knee joint articular cartilage thickness maps before and after applying physiologic loading can be generated using a 3D reconstruction process. We also hypothesized that total meniscectomy results in greater loss of articular cartilage thickness centrally, and less change peripherally.

METHODS
Sample Preparation: A sheep (24 months old, 50kg) leg was frozen at a 45 degree knee flexion angle. The entire knee joint was then cored with a 4.5cm hole-saw from the medial to the lateral side. This cylindrical specimen, which contained the entire tibio-femoral joint, the menisci, and the collateral and cruciate ligaments, remained frozen during the coring process and until testing.

Loading Device: A cylindrically shaped custom-made pneumatic loading device (6cm OD, 14cm long) and a custom air flow control box were designed and fabricated. The loading device consists of an outer cylinder, a supporting shell, a loading shell, and an air bladder (5cm x 5cm). The two shells and the cylinder were made with high mechanical quality cast acrylic, and the air bladder was manufactured from urethane coated nylon using a RF welding process (Figure 1). Inside the flow control box, a solenoid valve is controlled by custom designed electronic circuit to provide a static or a cyclic (1Hz) pressure. We applied two times of body weight across the tibio-femoral joint [3,4] which corresponds to 0.4MPa (60psi) of air pressure inside the air bladder.

MR Imaging: Prior to imaging, the sample was bathed in 5mmol/L gadolinium (Magnevist, Schering Ag, Berlin, Germany) solution for 12 hours. The intact knee sample was then scanned. Following this, the air bladder was inflated, applying a 2xBW static compressive force across the joint. After two hours of loading to achieve steady-state deformation [5], the statically loaded knee sample was scanned. The load was then removed, and after 24 hours to allow for full cartilage thickness recovery, both of the menisci were carefully removed, the joint was again loaded as before, and scanning was performed. Imaging was performed on a Unity Inova console (Varian, Inc., Palo Alto, CA) controlling a 4.7T, 15cm horizontal bore magnet (Oxford Instruments, Ltd., Oxford, UK) with GE Techron Gradients (12G/cm) and a volume coil with an inner diameter of 6cm (Varian, Inc., Palo Alto, CA). Scout images oriented coronal to the joint were performed to visualize the extent of interest. Fifty-five images oriented sagittal to the joint were planned from these images and acquired with a spin echo sequence (TR/TE 1850/20ms; matrix 1024 x 1024; FOV 6cm x 6cm; slice thickness 1mm; NEX 2) providing 58um x 58um in plane resolution. Total acquisition time for one sample was 63 minutes.

3D Reconstruction: Custom software [6] and GeoMagic (Raindrop Geomagic, Inc., Research Triangle Park, NC) were used for image segmentation, 3D surface generation, and cartilage thickness mapping. Only the femoral articular cartilage was mapped in this study.

RESULTS
Figure 2 shows the position of the menisci (white) in relation to the femoral articular cartilage (blue), and cartilage thickness maps for the intact knee without loading, with static loading, and with meniscectomy and static loading. With the meniscus intact, a broad area of articular cartilage is deformed under load, and this area corresponds to the area of meniscal contact. In contrast, when the meniscus is removed, a smaller area of cartilage is deformed to a greater extent due to direct contact with the tibial condyle, while the femoral articular cartilage that would have been in contact with the meniscus remains relatively undeformed.

DISCUSSION
We have demonstrated that an entire joint can be loaded to physiologic levels and imaged under load in a high field MRI scanner and that three dimensional maps of the articular cartilage deformation can be obtained. In this preliminary study, a static load was selected. The static loading condition of this study resulted in a greater magnitude of cartilage thickness loss than has been seen in patellar cartilage after cyclic loading [7]. Future work will incorporate cyclic loading, numerical modeling of the articular cartilage layer, and an investigation into the regional structural and biological changes under normal and meniscectomy conditions.

We found that the meniscus causes a broad area of articular cartilage to be deformed. Removal of the meniscus results in a smaller area of articular cartilage deformation and higher peak deformation. This novel technique involving three dimensional imaging and direct measurement of an intact and mechanically loaded joint will be useful in studying the mechanical etiology of osteoarthritis. Alteration in the normal pattern of articular cartilage deformation as we have seen with meniscectomy may be responsible for the development of osteoarthritis.

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REFERENCES