Positional Reproducibility of a Displacement Controlled MRI-Compatible Loading Device To Assess In Vivo Articular Cartilage Deformation

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Target Audience: MRI radiologists and scientists, and orthopaedic surgeons with an interest of magnetic resonance imaging (MRI) of knee joint cartilage.

Purpose: MRI has been used to assess articular cartilage thickness (1), cartilage morphology (2), and the biochemical content and structure of the tissue non-invasively (3), but the relationship between these metrics and the corresponding cartilage mechanics has not yet been completely evaluated. It has been suggested that the extent and location of articular cartilage deformation within a joint may be predictive of cartilage health and predisposition to further degeneration (4); however, in vivo quantification of articular cartilage deformation using MRI under controlled loads, and sequentially over time with the patient in the same position and orientation is technically challenging.

The objective of this study was to design an MRI compatible device capable of applying controllable axial loads while ensuring a repeatable tibiofemoral positioning and measurement of cartilage thickness.

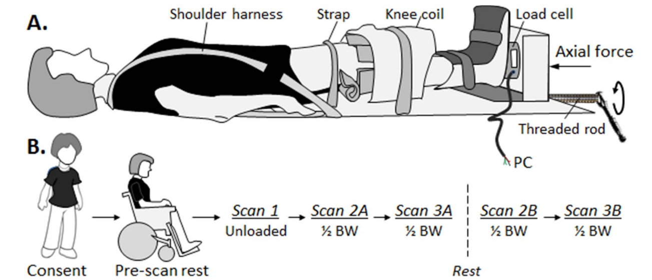

Figure 1. (A) Illustration of the loading device. (B) Time schedule for unloaded and loaded image acquisition.

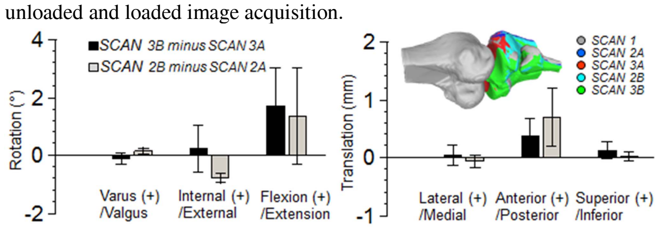

Figure 2. (Left) Tibial rotation and (Right) translation at different scans.

Methods: Loading device: The device is an MR compatible position controlled apparatus consisting of a stationary base and a mobile unit (Fig. 1A). The mobile unit is connected to the base by a threaded titanium rod to permit only axial translation. A 6-axis MRI compatible load cell (JR3 Inc., Woodland, CA) is attached to the mobile unit to record forces and torques. The load cell position is adjustable in the medial/lateral and anterior/posterior directions to ensure an axial-only load. Shoulder harness and straps are used to prevent the upper body motion. Forces are collected at 10 Hz using custom written software (MATLAB, MathWorks, Inc.). Participants: Four healthy volunteers with no diagnosis of knee osteoarthritis or history of lower limb injuries participated in this study. This study had IRB approval and written informed consent was obtained. MRI acquisition: Volunteers were placed in a wheelchair for 30 minutes prior to image acquisition. A 3D SPGR frequency selective fat saturation image series were performed on a clinical 3T scanner (GE Healthcare, Waukesha, WI) using an 8 channel phased array knee coil (Invivo, Gainesville, FL). Scanning parameters were: TE/TE = 3.2/15.4 ms, field of view = 14 cm, slice thickness = 1.5 mm, acquisition matrix = 512×512, number of excitations = 1, flip angle = 20°, voxel dimensions = 0.27×0.27×1.5 mm, scan time=7:52. Five sequential scans were performed (Fig. 1B). *Scan 1* - baseline images with the knee in an unloaded configuration at full extension. *Scan 2A* - a load equivalent to 50% of the participant's body weight (BW) was applied to the imaged knee via a ratcheting mechanism. A settling period of 2 minutes was permitted and the load was increased back to 50% BW to compensate for any tissue relaxation just prior to the scan. *Scan 3A* - the axial force was then adjusted back to 50% BW and the scan was repeated. The subject was removed from the scanner and an approximate 15-minute rest period was allowed with the imaged knee unloaded. Finally, the Scan 2A and Scan 3A were repeated, labelled as *Scan 2B* and *Scan 3B* respectively, to assess the repeatability of the knee position and the effect of pre-loading time on cartilage deformation. Data Analysis: Images were manually segmented (ITK-SNAP) (5) to create 3D models of bone and articular cartilage surfaces. The femur segmentation of 2A, 3A, 2B and 3B were registered to the corresponding segmentation of the unloaded images using an iterative closest point (ICP) shape matching algorithm. The changes in tibial position between two repeated scans were calculated with respect to femoral coordinate system. Cartilage thickness was calculated as the shortest distance from the subchondral bone surface to the corresponding articular cartilage surface. Region of interest (ROI) was selected as the contact region between tibial and femoral cartilages. Cartilage deformation within the ROI upon loading was calculated as the difference in thickness (loaded minus unload) after aligning the subchondral bone surface of different scans. The results at two repeated conditions (*Scan 2A vs. Scan 2B, Scan 3A vs. Scan 3B*) were compared. *Segmentation Repeatability*: Four repeated segmentations were performed on the same MRI scan by the same individual and the RMS error of cartilage thickness within the identified contact region was evaluated.

Results: Axial force of 50% BW was maintained throughout the scanning period, with a 12.1%, 12.0%, 11.1%, and 9.0% reduction in force measured for scans 2A, 2B, 3A, and 3B, respectively. The average change in tibial position between two repeated scans was limited: < 0.2 mm in both the medial/lateral and superior/inferior translation and < 0.8 mm in anterior/posterior translation; < 0.4° in varus/valgus rotation, < 1° in internal/external rotation, and < 2° in flexion/extension (Fig. 2). The differences in internal/external rotation and anterior/posterior translation between *2A* and *2B*, 0.8° and 0.8 mm, respectively, were greater than those between *3A* and *3B*, whereas in flexion/extension the difference was slightly smaller between *2B* and *2A*. The force applied during *3A* and *3B* was more consistently maintained than that during *2A* and *2B*, when the knee had only been loaded for 2 minutes prior to image acquisition. The differences in cartilage deformation were smaller between *3A* and *3B* compared to those between *2A* and *2B*, with a decrease in cartilage thickness occurring within the contact region upon loading. The segmentation repeatability analysis found the minimal detectable change of the average cartilage thickness within the contact region to be 0.078 mm.

Discussion: We demonstrated the feasibility of using an MRI compatible displacement-controlled loading device to apply a consistent axial load, while maintaining controlled femoral-tibial positioning when acquiring MR images on four volunteers. The repeatability test showed repeatable knee position across different scans, to within 1 mm of translation and 2 degrees of rotation. Cartilage thickness decreased in response to the applied load, indicating stress relaxation of the tissue. In addition, the greater reproducibility of thickness measurements found when the cartilage was loaded for 12 minutes prior to scanning suggests that the articular cartilage may have approached steady-state of deformation at this time point.

Conclusion: An MR compatible positioning device is capable of repeatable tibiofemoral joint positioning, and reproducible measurements of cartilage deformation under loading are obtained by pre-loading the lower limb for at least 12 minutes.

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