Full-Field Strain Characterization of Patellar Cartilage Following Osteochondral Allograft Transplant Using MRI Methods

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INTRODUCTION: Articular cartilage is a connective tissue that is found in diarthrodial joints, where it facilitates locomotion of the joint by providing a low-friction surface. Articular cartilage injuries are present in up to 66% of knees undergoing cartilage diagnostic procedures for knee pain, where 20% of these lesions are observed in the patella. Full cartilage thickness defects have a prevalence of up to 6.2% in the general population but increase to 36% in athletes. Chondral lesions in the patellofemoral joint (PFJ) may occur due to recurring dislocation, traumatic injury, osteochondritis dissecans, and cartilage degeneration. Due to articular cartilage having limited repairability, osteochondral allograft (OCA) transplants have been used to treat full-thickness cartilage injuries in PFJ. Despite having advantages such as a single-stage operation and the ability to treat larger defects in the PFJ, the OCA procedure in the patella is associated with failure at 20% and reoperation at 52% after 15 years following the procedure. The compression-induced mechanical changes following an OCA procedure in the patella are unknown. Using finite element analysis, we have previously shown that high strain regions (HSR) are generated in the interface between the donor and recipient cartilage when mismatched cartilage thickness is present following an OCA procedure. In this study, we aim to utilize a novel magnetic resonance imaging (MRI) technique to obtain the displacement and strain fields of OCA-repaired patellae during compression of articular cartilage. We hypothesize that HSR will emerge at the interface between the donor and recipient cartilage, which may elucidate the possible mechanisms of the high patella OCA failure rates.

METHODS: To evaluate the full displacement and strain fields of the articular cartilage of the patella, *ex-vivo* compression tests were performed on cadaveric patella samples. Intact left cadaveric knees (n=4, 3 male and 1 female knee. Age: 36.3 years $\pm$ 12.0 years) were thawed, hydrated in 1X phosphate-buffered saline, and prepared for mechanical testing. For the OCA sample preparation, one of the samples was chosen to be the donor and the remaining samples were categorized as recipients. A 19.1 mm OCA graft was removed from the donor sample, and was later trimmed to a height of ~8 mm. In the recipient samples, a 17.46 mm diameter hole of 8 mm depth was performed to transplant and press fit the OCA sample into. Patellae samples were first tested in the intact configuration. Later the samples that went through the OCA procedure were tested using the same parameters. A 25.4 mm diameter indenter was fixed to the imaging chamber, while an extracted 44.5 mm patella core was attached to a translating fixture. The displacement of the fixture was controlled and applied using a computer-driven stepper motor. The sample was placed in a 60 mm radiofrequency coil and placed in a 7 T magnetic resonance imaging (MRI) machine. A precondition step of 1 mm displacement at 0.33 Hz was performed for 10 minutes prior to the start of the tests. The samples were tested at two different load-unload cycles synchronized to a custom displacement encoded MRI sequence called APGSTEi (Alternating Pulsed Gradient Stimulated Echo Imaging). An encoding wavelength, λ, of 1 mm was used for the compression sequences of 1 mm and 2 mm. The images were obtained on a low-resolution acquisition grid of 96x32x24 voxels with a voxel dimension of 0.33 mm x 1.5 mm x 2.0 mm. A high-resolution anatomical dataset was acquired prior to each loading sequence using a conventional 3D gradient echo sequence, at a resolution of 196x128x128 voxels and voxel sizes of 0.17 mm x 0.38 mm x 0.38 mm.

RESULTS: Full field displacement maps were obtained for all samples for both the 1 mm and 2 mm displacements in all three spatial directions. The minimum principal strain and maximum shear strains were also quantified across the articular surface. Mean forces for the 1 mm displacement were 60.8 N $\pm$ 12.4 N, while for the 2 mm displacement, it was 120.3 N $\pm$ 27.3 N. Figure 1 contains the displacement observed for the 2 mm cyclic displacement in the center slice of the MRI image sequence. Figure 1 also contains the interpolated data from the articular cartilage into a sample-specific 3D mask. This process was also done for the displacements in each spatial direction and the outcomes of interest. Displacement distributions were relatively uniform and were the expected contour for a spherical indenter. The expected contours were also observed in the other 2 directions (displacement in Y and Z). After OCA transplantation, strain fields remained heterogeneous among samples with no localized HSR observed in the donor-recipient cartilage interface under the applied loading conditions. Despite the lack of noticeable HSR, the minimum principal strain (Figure 2 – top row) and maximum shear strain (Figure 2 – bottom row) at corresponding locations before and after transplantation confirmed small but measurable differences. The values from these outcomes of interest were quantified as a function of both the value of the in the intact sample to the value of the strain in the OCA-treated sample and the "step off" distance, which was described as the distance from the subchondral bone of the recipient sample to the subchondral bone of the donor graft.

DISCUSSION: Our results show our novel MRI-based displacement encoding technique is successful at capturing and obtaining the full-field mechanical response of intact and OCA-treated patellae samples under controlled compression. Minimum principal strains and maximum shear strain values were obtained at the donor and recipient sites around the whole graft geometry. However, contrary to our initial hypothesis, distinct HSR at the donor-recipient interface were not observed under the applied loading protocol.

Several factors may explain these outcomes. First, the applied loads ($\leq$ 120 N) may not be sufficient to generate the elevated stress previously shown in our research. Second, testing was limited to the use of a 25.4 mm diameter indenter rather than a full volumetric compression of the articular cartilage surface or simulated compression of the contact between the femoral groove and the patella cartilage at certain knee flexion angles. Finally, the small sample size and the use of long frozen cadaveric tissue may have contributed to variability in the biomechanical response of the cartilage.

Despite these limitations, this study establishes a reproducible framework for *ex*-vivo full-field displacement and strain mapping in the patella in before and after OCA transplantation. Future work incorporating physiological joint loading conditions, larger sample sizes, and improved tissue quality is necessary to evaluate and quantify the HSR at the strain concentration at the donor-recipient interface and how they may impact the elevated long-term OCA failure rates in the PFJ.

SIGNIFICANCE/CLINICAL RELEVANCE: Describing the full-field strain distribution in the patella following an OCA transplant provides insight into the mechanical factors that may underlie the high graft failure rates in the PFJ. Identifying the point at which high-strain regions develop between the donor and recipient cartilage can help guide surgical protocols, graft selection, and rehabilitation strategies to improve long-term outcomes.

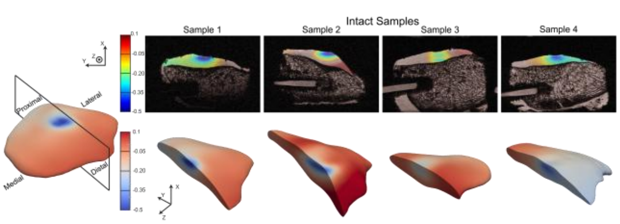

Figure 1: 2D Slice disp. in X

3D Mask with full field disp. in X

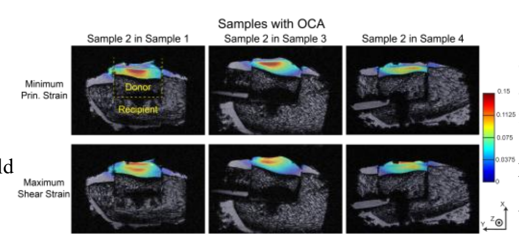

Figure 2: Outcomes of interest in a 2D slice of the patella samples with OCA