A Framework for Quantifying Tibial Cartilage Deformation After Activity *In Vivo* via MRI

Sebastian Scofield[1, 2], Benjamín A. Rodríguez Romo[1,3], Christopher Sica[1], Jorge Chahla[1], Philip Malloy[1], John Martin[1], Catherine Yuh[1], Steven P. Mell[1]
[1]Rush University, Chicago, IL, [2]Chicago Medical School, North Chicago, IL, [3]Universidad Adolfo Ibáñez, Campus Viña del Mar, Chile
Sebastian.scofield@my.rfums.org

Disclosures: SS (N), BRR (N), CS (3B- Neurona Therapeutics), JC (3B- Arthrex Inc., CONMED Linvatec, Ossur, Smith & Nephew; 9- AAOS, AANA, ISAKOS), PM (N), JM (N), CY (N), SPM (N).

INTRODUCTION: In the knee, cartilage undergoes mechanical stress and strain as a result of daily activity. Abnormal contact at the cartilage interface may occur with joint pathology, such as altered tibiofemoral alignment or meniscal injury, leading to uneven load distribution and focal stress on the tibial articular surface. It is well established that excess cartilage contact stresses that may occur in such pathologies are associated with tissue damage and subsequent deterioration [1-3]. However, direct *in vivo* quantification of cartilage contact mechanics (e.g., stress and strain) remains a challenge [4,5], due to both ethical and technical limitations. This preliminary study presents a reproducible magnetic resonance imaging (MRI) based segmentation and modeling framework to quantify tibial cartilage thickness change as a result of physical activity using 3D Slicer [6]. The research goals of this study were: 1) Directly quantify tibial cartilage compression after 60 minutes of walking and 2) Compare the DESS and T1 VIBE FLASH sequences in terms of generating high fidelity segmentations for assessing cartilage thickness changes before and after activity.

METHODS: Three healthy adult subjects (2 male, 1 female) participated in an MRI-based study of tibial cartilage deformation. Each subject rested supine for 60 minutes before undergoing a baseline 3T MRI knee scan using a sagittal DESS and T1 VIBE FLASH sequence. Subjects then underwent 60 minutes of continuous treadmill walking at a self-selected, sustainable brisk pace, instructed to maintain a limb-length-normalized velocity corresponding to a Froude number of 0.25 [7], followed immediately by a second MRI scan (**Figure 1**). Subject 1 (male) underwent post-activity MRI using the DESS sequence, while Subjects 2 (male) and 3 (female) underwent FLASH. Tibial bone and cartilage surfaces were manually segmented from both pre- and post-walking scans using 3D Slicer software (**Figure 2A-C**); with the same MRI sequence used at both timepoints to ensure consistency for deformation analysis. Segmentation workflow included using an oversampling factor of 1.5, with initial model generation performed in the sagittal plane, followed by refinement in axial and coronal views. Joint smoothing (0.8) was applied, followed by a second round of multi-planar review to correct residual artifacts, and finalized with an additional joint smoothing (0.7). Rigid Iterative Closest Point (ICP) registration [8], with 350 iterations, aligned the post-walking tibial bone model to the pre-walking bone model. The resulting transformation matrix was then applied to the post-walking cartilage model, ensuring consistent spatial anatomical alignment with the pre-walking cartilage model. Cartilage thickness change was quantified by computing signed Hausdorff distance between the two models using a 3D Slicer extension "ModeltoModel Distance" [9]. Compression-only deformation maps were visualized by thresholding to include only positive deformation (compression). Peak deformation values were extracted using Python within 3D Slicer via a multi-step filtering process that excluded outer boundaries, low-density mesh areas, high-curvature artifacts, and internal edge-like discontinuities to reduce noise and prevent overestimation. For code verification, a separate, custom Python script using ICP and signed Hausdorff distance was developed to calculate deformation and compared to 3D Slicer results.

RESULTS: FLASH enabled clearer segmentation at tibial cartilage edges, potentially reducing peripheral noise, while DESS offered clearer distinction between tibial and femoral cartilage contact points and better visualization of synovial fluid. Bone segmentation was marginally easier in FLASH, with clearer visualization of tendon and ligament insertions on the tibia. Deformation maps generated in 3D Slicer showed no qualitative differences from those produced with our custom Python code, supporting reproducibility. Cartilage compression on the tibial plateau was observed in all subject knees after 60 minutes of activity. Model-to-model distance analysis revealed measurable compression in weight-bearing regions on the tibia showing clearly defined areas of contact. Subject 1 (male) showed the greatest cartilage thickness change, with prominent medial tibia compartment deformation (peak: 1.05 mm) and less in the lateral compartment (**Figure 3A**). Subject 2 (male) exhibited more centralized medial compartment deformation (peak: 0.92 mm) compared to that of Subject 1, with a radial gradient of decreasing compression; lateral compartment cartilage showed diffuse loading without focal displacement (**Figure 3B**). Subject 3 (female) displayed more localized deformation compared to both Subjects 1 and 2, with peak compression (0.70 mm) in the central lateral tibia cartilage and two distinct contact zones. Medial deformation was lower, with the remainder of the compartment near baseline (no compression) (**Figure 3C**).

DISCUSSION: This proof-of-concept study demonstrates the feasibility of using MRI and image registration to quantify tibial cartilage deformation *in vivo* following a controlled walking task. The observed reductions in cartilage thickness are consistent with prior reports of load-induced strain, providing preliminary verification of the sensitivity of this approach [10]. Spatially localized deformations, particularly in weight-bearing regions (**Figures 3A–C**), reveal distinct delineation of contact areas; however, further assessment with additional subjects is necessary to validate these patterns. Despite the limited sample size, findings suggest that contact patterns between individuals are highly variable. This variability may be driven by anatomical differences (e.g., femoral cartilage counterface shape, meniscal involvement) and biomechanical variation in gait – both of which will be the focus of future work. Additional limitations include segmentation time (~15 hours per tibia and tibial cartilage), sample size, and inter-subject repeatability. Still, this pipeline lays groundwork for studying the effect of activity on cartilage contact variables, including future assessment of femoral cartilage deformation, incorporation of joint motion as a dynamic parameter, validation of *in silico* models of tibiofemoral joint contact, and integration with finite element analysis (FEA) to model tissue-level stress responses. While preliminary, this method demonstrates that cartilage thickness deformation can be computed at the resolution of the segmentation, potentially offering higher fidelity than previous interpolation-based approaches [11]. However, the increased sensitivity to noise underscores the need for continued refinement and validation before clinical interpretation, especially given that this study did not quantify inter-segmentation noise.

SIGNIFICANCE/CLINICAL RELEVANCE: This framework enables direct, *in vivo* measurement of cartilage deformation, offering new insight into load-induced tissue remodeling and laying the groundwork for predictive models of joint degeneration and for broader musculoskeletal assessment.

REFERENCES: [1] Akanda MR, *et al*. Ann Biomed Eng. 2025;53(2):192–204. [2] Mahendra A, *et al*. Malays J Med Health Sci. 2025;21(2):112–117. [3] Masson AO, *et al*. BMC Musculoskelet Disord. 2020;21:363 [4] Chan DD, *et al*. Sci Rep. 2016;6:19220 [5] Deneweth JM, *et al*. J Orthop Res. 2013;31(3): 370–375 [6] Fedorov A, *et al.* Magn Reson Imaging. 2012;30(9):1323–1341 [7] Alexander RMcN, *et al.* Journal of Zoology. 1983;201(1):135–152. [8] Ungi T, *et al*. Med Image Anal. 2016;33:181–186 [9] Budin F, *et al*. https://www.slicer.org/wiki/Documentation/Nightly/Extensions/ModelToModelDistance [10] Rovedo P, *et al.* J Magn Reson Imaging. 2023 [11] Paranjape CS, *et al.* Sci Rep. 2019;9:2283.

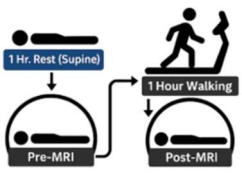

Figure 1. *Schematic timeline illustrating the MRI acquisition protocol before and after walking.*

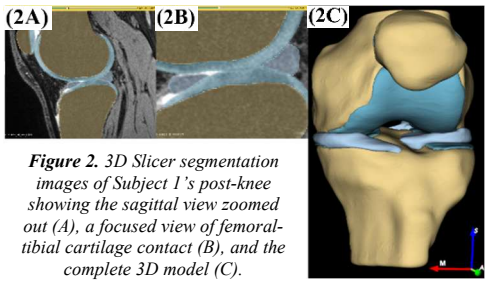

Figure 2. *3D Slicer segmentation images of Subject 1's post-knee showing the sagittal view zoomed out (A), a focused view of femoral-tibial cartilage contact (B), and the complete 3D model (C).*

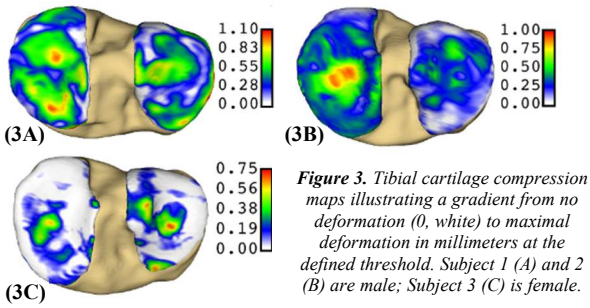

Figure 3. *Tibial cartilage compression maps illustrating a gradient from no deformation (0, white) to maximal deformation in millimeters at the defined threshold. Subject 1 (A) and 2 (B) are male; Subject 3 (C) is female.*