Effect of Loading Magnitude on the Wear Behavior of Bovine Meniscus

Kate J. Benfield, Katherine J. Fors, Trevor K. Black, Karlee M. Macaw, Trevor J. Lujan
Boise State University, Boise ID
katebenfield@u.boisestate.edu

Disclosures: The authors declare no conflicts of interest.

INTRODUCTION: The repetitive wear-and-tear of knee menisci plays a significant role in chronic knee pain and disability, yet little is understood about the mechanical factors that govern this degenerative process. Meniscal degeneration impacts over 55% of people over 70 years of age,[1] and is characterized by weakened and frayed extracellular matrix (ECM) fibers leading to symptoms including pain, joint instability, and an increased risk of developing osteoarthritis (OA).[2] Efforts to understand knee degeneration have been largely focused on OA in articular cartilage; however, meniscal degeneration has recently been suggested to precede knee joint cartilage degeneration.[3] Therefore, a critical need exists to identify mechanical factors that influence meniscal wear-and-tear, with the ultimate goal of preventing the onset of knee OA. One primary mechanical factor that influences wear behavior is loading magnitude (contact stress). In vivo variations in meniscal loading will occur due to many intrinsic (e.g. joint anatomy) and extrinsic (e.g. body weight, body-borne loads, and daily activity[4]) factors, yet the sensitivity of meniscal wear resistance to the magnitude of the applied load is unknown. The objective of this study was to therefore characterize the effect of loading magnitude on meniscal wear behavior.

METHODS: Femoral cartilage plugs (n = 10; 4 mm diameter) and meniscus (n = 5) were extracted from skeletally mature bovine stifle joints for testing. Each meniscus was sectioned into anterior and posterior regions, flattened using custom-made tooling to allow for a uniform surface, and cut into 2 mm thick layers[5] (25 mm x 15 mm). The superficial layers were used for ten experiments consisting of two groups: low (8N) and high (12N) compressive loading (n = 5/group), corresponding to walking and jogging, respectively.[4] Custom built pin-on-plate mechanical test systems applied reciprocating motion by translating the meniscal plate (2 Hz, 5 mm stroke)[6] relative to the fixed cartilage pin **(Fig 1A).** The meniscus plate was first clamped into the detachable test platform **(Fig 1B)**, imaged via a 3D optical scanner to generate a pre-test 3D model,[7] and inserted into the tissue chamber filled with PBS solution[8] **(Fig 1A)**. Using weights, vertical loads were applied between the cartilage and meniscus **(Fig 1A)**. Linear displacement (viscoelastic creep + permanent deformation) of the meniscal tissue was measured over 20,000 cycles using a displacement sensor (accuracy = 1 μm). Following wear testing, each meniscus plate was imaged to generate a post-test 3D model,[7] and then after a 2h unloaded recovery period in a PBS bath (21C), the plate was imaged once more to generate a post-recovery 3D model.[7] 3D color maps were created by registering the pre-test model to the post-test and post-recovery models using a cubic registration block **(Fig 1B-C)**.[9] From pilot testing, a 2h recovery period fully recovered tissue deformation following creep testing with a 12N load (**Fig 1C**), thus surface deviations between the pre-test and post-recovery meniscal surfaces were considered to be due to wear and plastic deformation rather than creep. The effect of loading magnitude and number of cycles on linear displacement was assessed using a repeated-measures ANOVA (one sample from the low loading group was excluded due to being an extreme outlier). Separate independent samples t-tests were performed to detect any differences in steady-state displacement, maximum displacement, and linear wear values between loading groups.

RESULTS: The high loading condition had 1.7x greater linear wear within the wear region-of-interest (p = 0.17) **(Fig 1C-D)**, and significantly greater maximum linear displacement after wear testing (p = 0.01) **(Fig 1E)**. Steady-state linear displacement was achieved for low and high loading after an initial 6000 cycles (run-in) with average steady-state displacement rates of 1.57 μm/10^3-cycles and 2.91 μm/10^3-cycles, respectively (p = 0.31). Overall, the application of high magnitude loading increased the linear displacement of meniscus by 38% relative to low magnitude loading (p = 0.37) **(Fig. 1E)**.

DISCUSSION: For the first time, this study assessed the wear behavior of bovine meniscus subjected to repetitive loading and demonstrates the dependence of wear behavior on loading magnitude. An innovation of this work was that we utilized 3D optical scanning to quantify permanent deformation and to account for viscoelastic creep. Using this novel approach, we found meniscal wear under high loads (0.9 MPa), in comparison to low loads (0.6 MPa), to be nearly two-folds greater (0.22 mm to 0.13 mm). A prior pin-on-plate study (1Hz reciprocating motion, 86,000 cycles, 24h recovery) found linear wear between a cartilage-metal interface to be 0.15 mm and 0.09 mm for contact stresses of 1.0 MPa and 0.5 MPa, respectively.[10] While the testing parameters in this prior cartilage study differ from ours, it seems to indicate that meniscus has higher wear rates than cartilage. Furthermore, we found relatively small differences (38%) in linear displacement between low and high loading conditions **(Fig 1E)**. However, a greater difference (68%) in permanent deformation was observed following the recovery period **(Fig 1C-D)**. While more tests are needed, our results suggest that prolonged exposure to higher magnitudes of joint loading (i.e. body weight, body-borne loads, or specific activity) may be detrimental to the structural integrity of meniscus tissue.

SIGNIFICANCE/CLINICAL RELEVANCE: This study identifies loading magnitude as a mechanical factor influencing meniscus health, and serves as a baseline for future studies which could lead to clinical recommendations (e.g. exercise, movement techniques) to prevent and delay meniscal wear-and-tear.

REFERENCES: [1]Englund et al. *NEJM* (2008), [2]Englund et al. *Rad Clin* (2008), [3]Seitz et al. *FBB* (2021), [4]D'Lima et al. *PIME* (2012), [5]Wale et al. *JBE* (2021), [6]ISO-14243-3, [7]Benfield et al. *JMBBM* (2022), [8]Petersen et al. *Osteo Cart* (2023), [9]Benfield et al. *J Imag* (2023), [10]Lizhang et al. *JEM* (2011)

ACKNOWLEDGEMENTS: Funding kindly provided by grants NSF# 1554353 and NIGMS# P20GM109095.

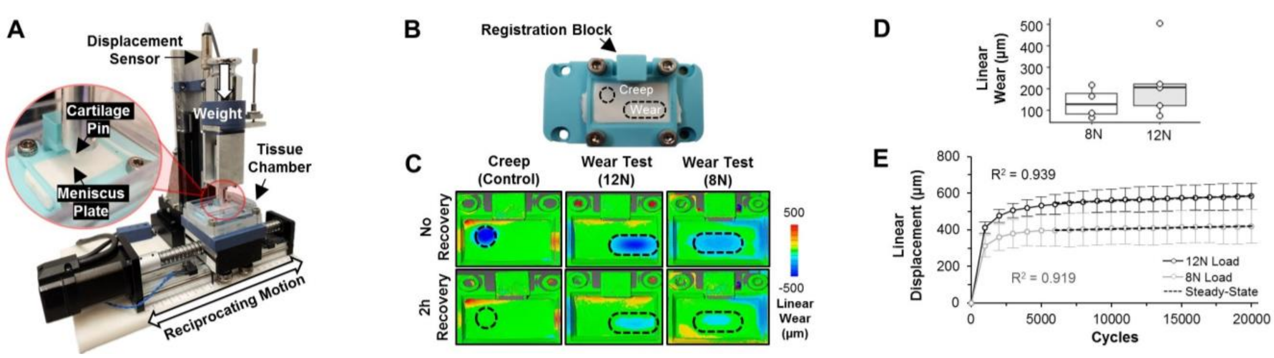

Figure 1: Pin-on-plate experiments. **A)** Our custom pin-on-plate test system applied reciprocating motion under various loads to meniscal tissue that was **B)** clamped within a detachable test platform. **C)** 3D optical scanning was used to generate color maps to visualize and **D)** quantify linear wear (permenant deformation) following a 2h unloaded recovery. **E)** The high loading magnitude (12N) resulted in greater maximum linear displacement (p = 0.01).