Multi-Structural Fibril-Reinforced Poro-Hyperelastic (MSFPH) Finite Element Modeling Approach for the Understanding of Articular Cartilage Pathomechanics

Md Saiful Islam[1] and Tanvir R. Faisal[1]

[1]Dept. of Mechanical Engineering, University of Louisiana at Lafayette, Lafayette, LA 70503

Email: tanvir.faisal@louisiana.edu

Disclosures: Md Saiful Islam (N), Tanvir R Faisal (N)

INTRODUCTION: Articular cartilage has a layered architecture comprising the heterogeneous organization of its constituents, which include heterogeneously distributed fluid and electrolytes, collagen fibrils, proteoglycans (PGs), and chondrocytes. Its extracellular matrix (ECM) can be considered as a fibril-reinforced composite solid consisting of heterogeneous network of type II collagen fibrils embedded in a PG matrix, which also contains chondrocytes surrounded by a thin layer called the pericellular matrix (PCM). The mechanical performance of cartilage is underpinned by its structure and the complex interactions between its constituents. Hence, the goal of the proposed work is to evaluate cell behavior in articular cartilage tissue and its constituents under mechanical loading.

METHODS: A physics-based approach has been adopted in this current study. We developed a novel multi-structural fibril-reinforced poro-hyperelastic (MSFPH) model study the mechanical response of the individual constituents. An axisymmetric finite element (FE) model was utilized, incorporating major cartilage ECM components such as collagen fibrils type II, PG matrix, PCM, chondrocytes (cells), and type VI fibrils in PCM. The varying orientations of the fibrils across three different layers—superficial, middle, and deep layers were accounted for in our model. The quasi-static finite element simulations were executed using the Abaqus/Standard solver. We considered the cartilage as a homogeneous isotropic material in our models. The CAX4P, a type of 2D axisymmetric porous finite element, was employed for the discretization of the structure. The model parameters included an unconfined compression of 0.24 mm over a 200 sec timeframe, simulating a strain of 20% at a strain rate of 0.1%/sec. The material model was implemented in Abaqus using the user-defined material script (UMAT) subroutine. Mechanical material parameters of ECM, PCM, and Cell were obtained from a previous study [1]. The pore pressure was calculated using Darcy's law (Eq. (1)), while permeability was assumed to be void ratio-dependent:

$$k = k_0 \left(\frac{1+e}{1+e_0}\right)^M \tag{1}$$

where k and k_0 denote current and initial permeability and e and e_0 denote current and initial void-ratio and M is the permeability void-ratio dependency constant. The initial void-ratio was set to 4. [2]

RESULTS: The proposed framework comprehensively examines the behavior of major cartilage ECM macromolecules during unconfined compression tests. At the superficial layer, the MSFPH model exhibits the maximum von Mises stress of 0.416 MPa, 0.092 MPa and 0.085 MPa for the ECM, PCM and Chondrocytes, respectively. The middle layer exhibits a lower level of stress at the ECM (0.379 MPa) and PCM (0.085 MPa). However, the chondrocytes in middle layer exhibit the maximum von Mises stress similar to the chondrocytes in superficial layer. The findings provide insights into the mechanics of individual cartilage ECM, PCM and cell under physiological loading conditions in Figs. 1 and 2. Furthermore, our model can capture the distinct stress profiles of collagen type II fibril networks.

DISCUSSION: Analysis of our findings indicates that tissue stress within the superficial zone is markedly elevated in comparison to the middle and deep zones. Stress peaks at 0.416 MPa in the articular cartilage's ECM, whereas the PCM experiences a reduced maximum stress of around 0.092 MPa, with further stress reductions observed as we transition to the deep zone. The superficial zone showcases an elevated tensile modulus for collagen fibrils, significantly surpassing that of the middle zone. Interestingly, stress patterns are virtually absent in the deep zone. A closer examination reveals that chondrocytes within the superficial zone undergo more pronounced volumetric shifts than their counterparts in other zones. Moreover, diverse deformation patterns in cells within identical zones under compression highlight the likelihood of varied mechanical stresses across cells in the same region.

SIGNIFICANCE: This research could be instrumental in promoting new treatments for degenerative diseases like osteoarthritis (OA), providing deeper insights into the mechanics of cartilage macromolecules and its role in OA progression. Current techniques, even with the aid of multiscale modeling, often focus solely on single components, neglecting their combined interactions. Our comprehensive model addresses this gap, emphasizing multiscale modeling's potential to enhance our understanding of complex biological systems.

REFERENCES: 1. Tanska P, Venäläinen MS, Erdemir A, Korhonen RK. A multiscale framework for evaluating three-dimensional cell mechanics in fibril-reinforced poroelastic tissues with anatomical cell distribution – Analysis of chondrocyte deformation behavior in mechanically loaded articular cartilage. *Journal of Biomechanics.* 2020/03/05/ 2020; 101:109648.
2. Shirazi R, Shirazi-Adl A. Analysis of articular cartilage as a composite using nonlinear membrane elements for collagen fibrils. Med Eng Phys. 2005 Dec;27(10):827-35. doi: 10.1016/j.medengphy.2005.04.024. Epub 2005 Jul 5. PMID: 16002317.

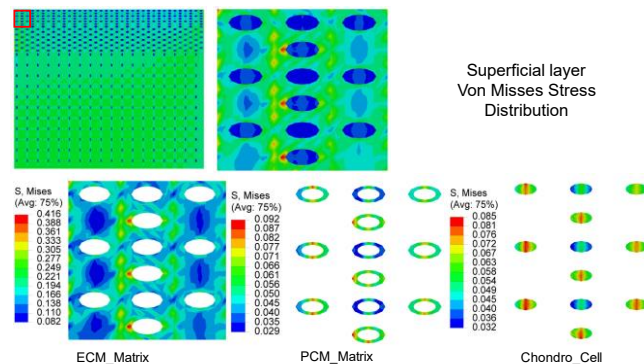**Fig 1:** Von Misses stress distribution of ECM, PCM, and Chondrocytes of superficial layer of articular cartilage.
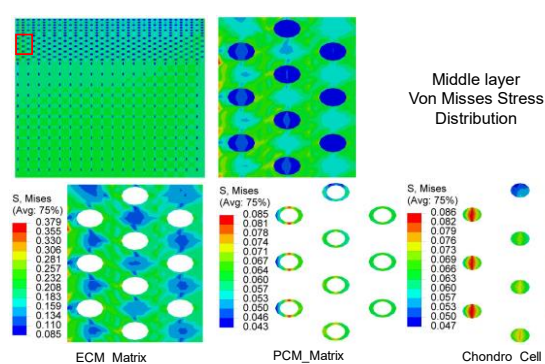

Fig 2: Von Misses stress distribution of ECM, PCM, and Chondrocytes of middle layer of articular cartilage.