Finite Element Analysis to Model the Effects of Osteoarthritis in the Knee

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INTRODUCTION

Significance and Background

- **Osteoarthritis (OA) is a degenerative disease that begins with the breakdown of the joint cartilage, and affects over half a million people globally [1,2]**
- **The presence of OA in the knee can lead to damage of the cartilage tissue, tendons, synovium, and bone, causing chronic pain, swelling, loss of motion, and may lead to excessive stress on the joint [1]**
- **Cartilage's avascular nature causes it to have a low regenerative capacity, because it does not have the blood vessels necessary to distribute the oxygen, nutrients, or white blood cells needed to stimulate healing [3]**
- **The subchondral bone (SB), calcified cartilage (CC), and articular cartilage (AC) provide mechanical support to the knee [4] (Fig. 1B)**
- **Pathological processes that affect the joints morphology or joint components, lead to changes in the biomechanics of the knee, and has been correlated to the presence of OA [1]**
- **Computational modeling with finite element analysis is used to stimulate and study complex systems with models. These models contain variables that characterize the system being studied, and can be adjusted to study the response from system [8]**
- **Understanding how knees with OA experience the stresses and strains from the compressional forces applied throughout everyday use is integral to engineering cartilage that is capable of replacing damaged tissue**

Study Objective and Hypothesis

- **The objective of this study is to use finite element analysis to model the subchondral bone and calcified cartilage interface, in order to quantify and analyze how the morphology of the interface, and presence of osteoarthritis affects the stress and strain distributions experienced by the knee.**
- **We hypothesize that the pathological changes experienced by knees with osteoarthritis will result in changes to how compressional loads are distributed across the calcified cartilage and subchondral bone interface, and will affect how and where the knee experiences these stresses and strains**

Our Approach

- **Develop specific and generalized models of the SB and CC in FEBio to conduct finite element analysis to determine if there are differences in the stress and strain distributions for healthy and OA**
- **Identify the regions of maximum stress and strain, and the magnitudes of those stresses and strains**

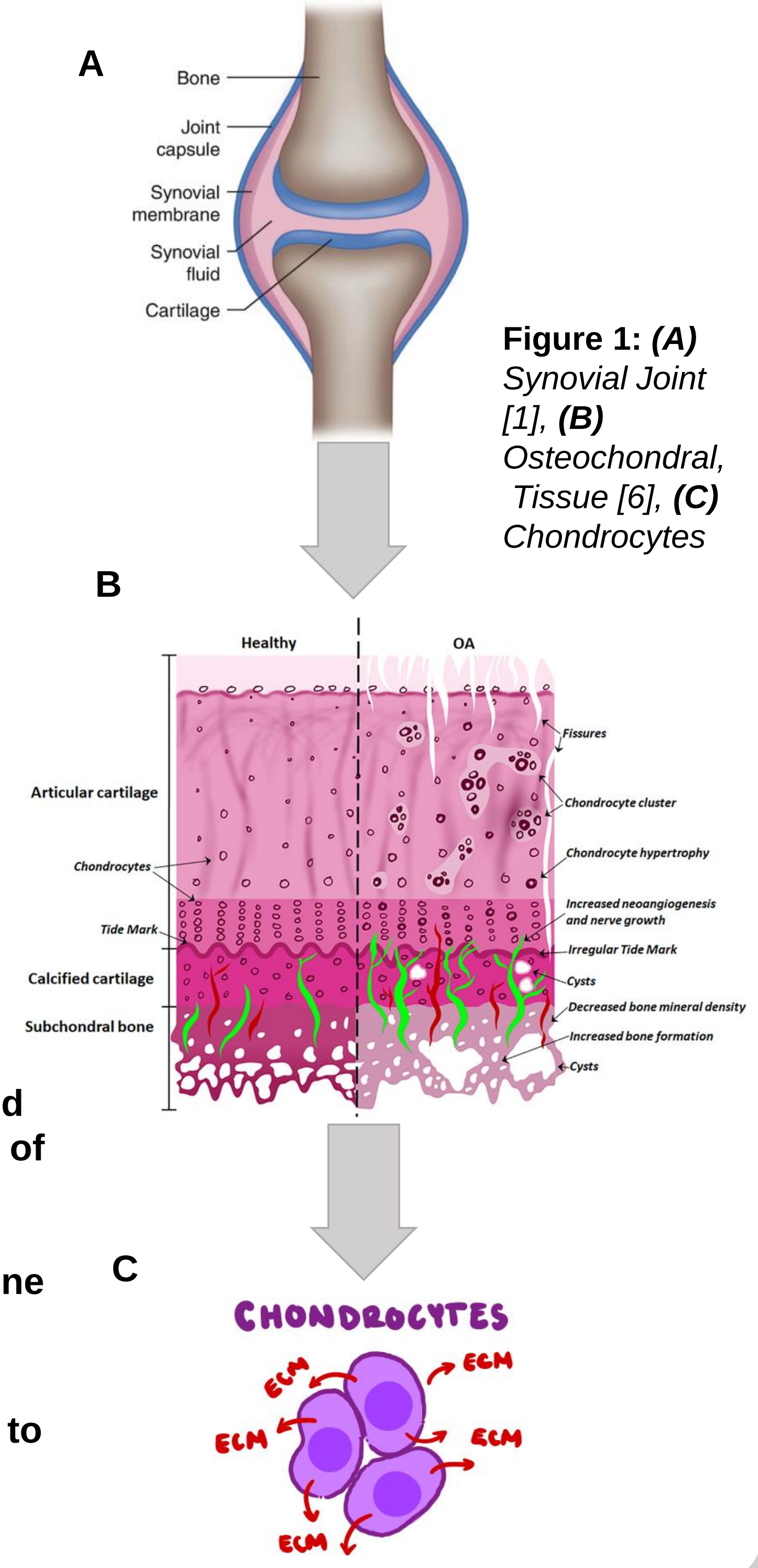


Figure 1: ***(A)*** *Synovial Joint [1],* ***(B)*** *Osteochondral, Tissue [6],* ***(C)*** *Chondrocytes*

MATERIALS & METHODS

Modeling

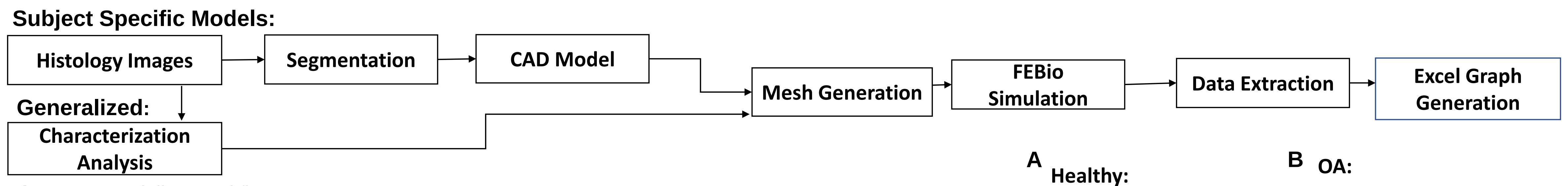


Figure 2 : *Modeling Workflow*

- **For this study, we developed both generalized models, and subject specific models, of the SB and CC interface to analyze if the stress and strain distributions vary between each group**

Generalized Models: n = 1

  - **The generalized models were created using averaged, subject specific data from the histology samples (Fig. 3A,B) where the dimensions of the model, and the shape and frequency of the undulations (Fig. 6) of the SB and CC interface were determined through histomorphometric analysis**

Subject Specific Models: n = 3

  - **The subject specific models were created using 2D histology images of the osteochondral interface of healthy and OA subjects to generate the 3D models in FEBio**
- **In order to analyze how the morphological differences between healthy and OA models affects the stress and strain distributions, the Young's Modulus, Poisson's ratio, and density between both groups were fixed**
- **Once the dimensions, material properties, and mesh size were determined, FEBio was used to generate the models**

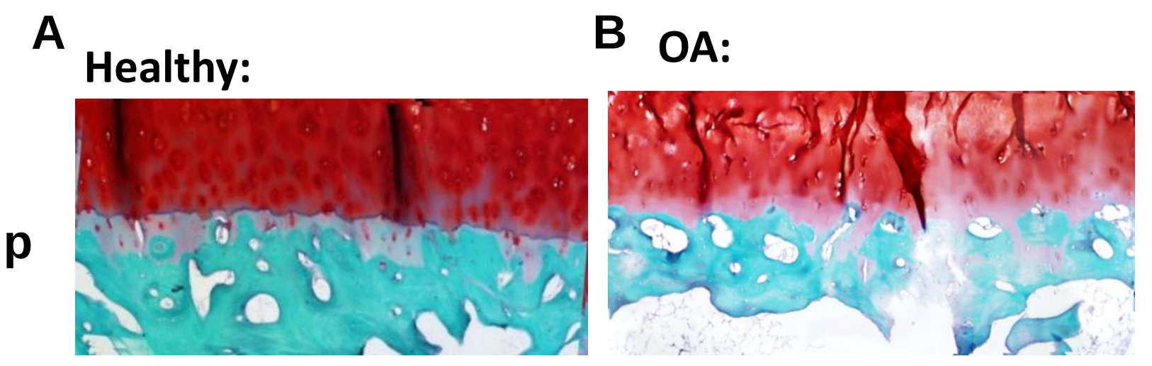


Figure 3: ***(A)*** *Healthy histology sample, and* ***(B)*** *histology sample with OA*

Table 1: *Material Properties*

	Young's Modulus (MPa)	Poisson's Ratio	Density (g/mm^3)
SB	2000	0.3	1.1
CC	320	0.4	1.2

Table 2: *Dimensions of Model*

	Dimensions
length (mm)	2.4
height (mm)	1.4

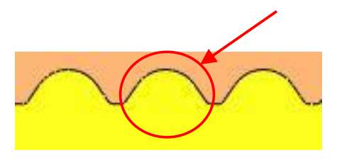


Figure 6: *Example of an undulation*

Evaluation

- **After the generalized and subject specific models were generated, a compression test was performed at 4 MPa on all models and the stress and strain colormap's were outputted, showing how the compressional load was distributed in each model**
  - **The 4 MPa compressional load was applied to top surface of model, the magnitude was determined was chosen based on physiological loading experienced in the knee when walking [7]**
  - **A confined compression test was performed, where the top and bottom of the model were fixed in all directions and all sides were fixed in direction of they are perpendicular to (Fig. 4)**
- **After the stress and strain colormaps were generated, the node IDs (Fig 5), their associated stress values, and the x, y, z positions were extracted from FEBio and imported into Excel to conduct further analysis on the stress distribution**

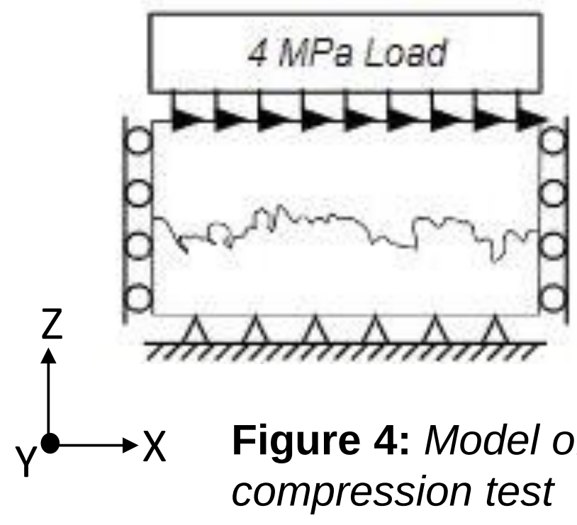


Figure 4: *Model of compression test*

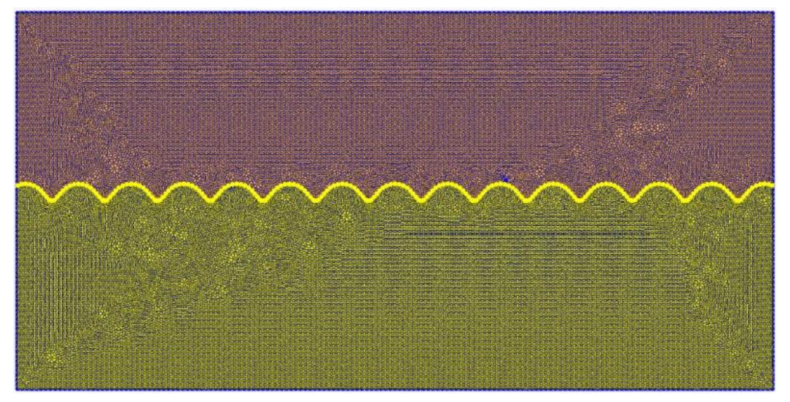


Figure 5: *Node IDs at the interface used for Stress graphs*

RESULTS

Strain Energy Density

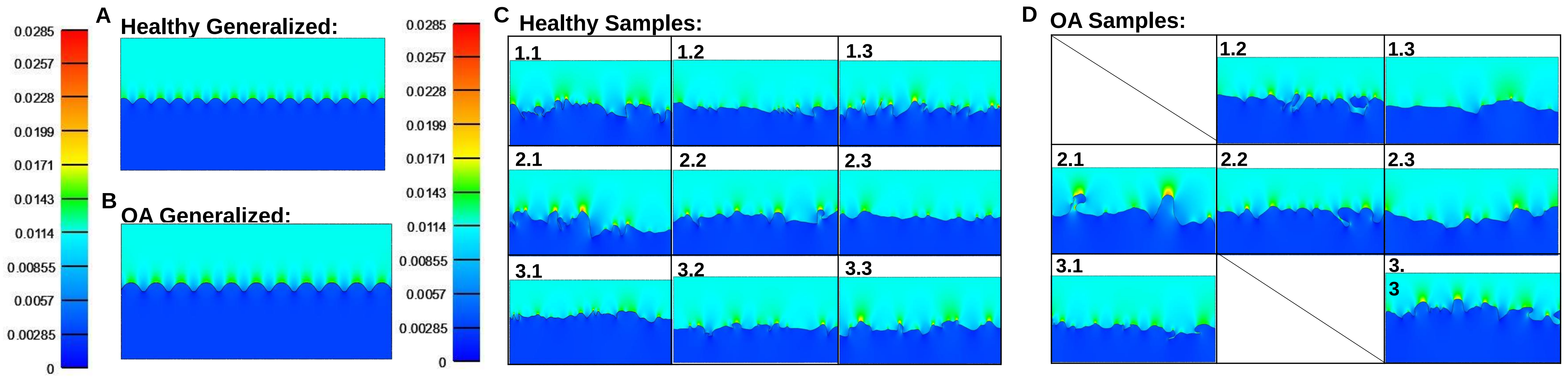


Figure 7: *Strain energy density (SED) of* ***(A)*** *healthy generalized model,* ***(B)*** *OA generalized model ,* ***(C)*** *healthy samples, and* ***(D)*** *OA samples under 4MPa compressional load*

- ***Strain energy density (SED)*** **measures the amount of energy per unit volume stored in a body due to deformation once a load is applied. The higher the SED, the more energy is able to be absorbed under elastic deformation. SED can also be thought of as a materials resilience.**
- **Regions with the highest SED occur at the peak of the undulations in the CC for both the healthy and OA groups**

Max Shear Stress

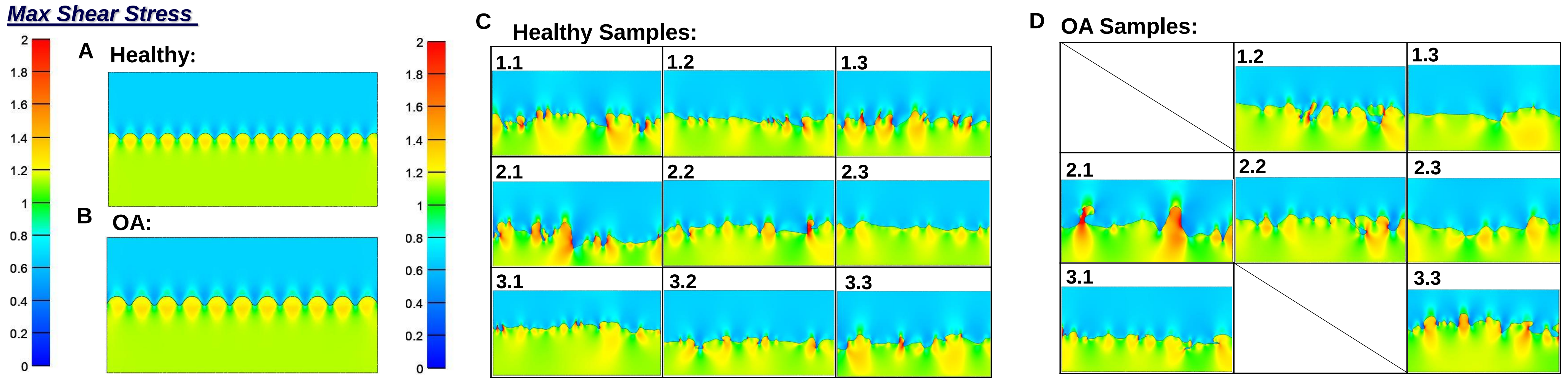
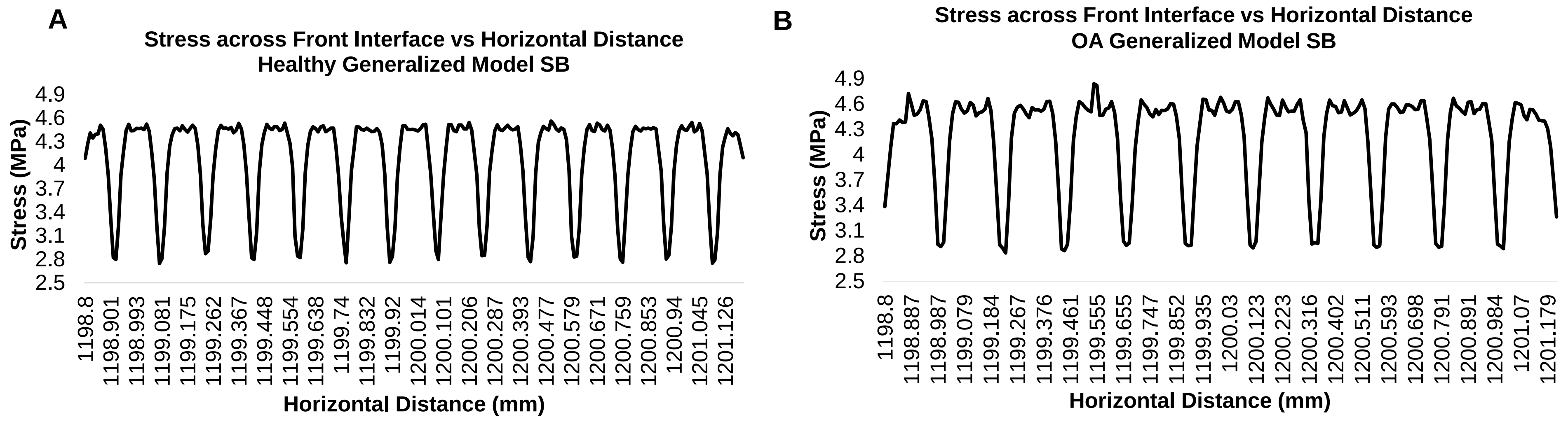


Figure 8: *Max shear stress distribution of* ***(A)*** *healthy generalized model,* ***(B)*** *OA generalized model ,* ***(C)*** *healthy samples, and* ***(D)*** *OA samples, under 4MPa compressional load, Note: The cutoff range for the colormap is 0-2 MPa all models to identify the regions experiencing the highest stresses*

- ***Maximum shear stress*** **is the maximum stress applied to the body due to a force acting parallel to its surface. A larger shear stress means the region is experiencing a larger force per unit area.**
- **Stress concentrations occur at the peak of the undulations in the SB for both the healthy and OA groups**
- **Size of the undulation correlates to the magnitude of stress applied to the undulation**

Stress Distribution



- **Stress distributions for healthy and OA groups follow the shape of the undulations**
- **Maximum stress is applied at the peaks of the undulations of the SB**

Figure 9: *Stress distribution across the horizontal distance of the SB interface for the* ***(A)*** *healthy and* ***(B)*** *OA generalized models*

DISCUSSION & CONCLUSIONS

- **The maximum strain energy density was experienced at the peak of the undulation of the calcified cartilage for both the healthy and OA group. This suggests that the CC is able to absorb the more energy from the 4 MPa compressional load without permanently deforming, which means it is more resilient than the SB, and it has the ability to spring back to it's original shape after a load is applied**
- **The maximum shear stress is experienced in the undulations of the subchondral bone for both healthy and OA groups, suggesting that the SB experiences higher stresses than the CC from the 4MPa load. This means that the SB is experiencing more stress per unit of area, and suggests that the SB is most prone to failure if excessive load is applied**
- **The stress distribution across the interface of the subchondral bone periodically follows the shape of the undulations for both the healthy and OA groups. This suggests that the shape and size of the undulation correlates to the magnitude of the stresses experienced in the region**
- **By analyzing the undulation size and shape, we can conduct critical area analysis to identify the regions that are most vulnerable to failure once a load is applied**
- **Identifying areas that are most prone to failure allows us to engineer cartilage that is capable of withstanding the compressional loads that are applied throughout everyday activity**
- **Further analysis of how fatigue loading affects the stress and strain distributions, along with the rate of deformation on the SB and CC interface, should be conducted**

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ACKNOWLEDGMENTS

The authors would like to acknowledge the funding and support from the Amazon Summer Undergraduate Research Experience (SURE) Fellowship and NSF DGE-2036197 (JZL), NIH 5R01AR073529 (HHL)