# USE OF ASPIRATION PRESSURE AND FINITE ELEMENT ANALYSIS FOR EVALUATING THE MECHANICAL BEHAVIOR OF ARTICULAR CARTILAGE

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## INTRODUCTION

Mechanical tests, such as confined compression, unconfined compression, tensile, shear, and indentation have been used in determining the behavior and biomechanical properties of articular cartilage [2-6, 8]. Compressive indentation testing is often preferred because it can be performed in situ and nondestructively [6]. In a recent study, a new experimental testing technique has been used to study the behavior of articular cartilage [1]. This nondestructive technique applies an aspiration pressure to the surface of a tissue, placing it in tension, and monitors the ensuing deformation. Similar testing has also been performed on cardiac tissue [7]. This study analytically evaluated the behavior of articular cartilage under an aspiration pressure with the finite element method.

## MATERIALS AND METHODS

Finite element analyses were performed using ABAQUS® (Warwick, RI) with its ability to model two phase materials. A 252 node, 210-element mesh with thickness h=0.584mm was developed to simulate the geometry and boundary conditions of the setup for an aspiration experiment. Elements were 4-node axisymmetric, isotropic quadrilaterals with bilinear displacement and bilinear pore pressure. A central region (radius of 3mm) of the cartilage surface was subjected to an aspiration pressure of 0.1MPa for the first 30sec interval, followed by a second 30sec interval for recovery with the pressure removed, to simulate experimental testing conditions with the aspirator [1]. The model was constrained at the cartilage-bone interface in the r and z direction, at the axis of symmetry (center region of aspirator) in the r direction, as well as in the z direction at the location where the aspirator makes contact with the articular surface. On the articular surface, the pore pressure was set to zero to allow fluid to exude from the tissue unhindered. Time steps of 0.05sec were implemented for the initial time dependent response (up to 1sec) followed by larger time steps of 0.1sec and 1sec until the 30sec interval was completed..

With the model constructed, several analyses were performed with different material properties assigned to the cartilage to understand its behavior under this new testing methodology. Different material values of aggregate modulus ($H_a$), permeability (k), and Poisson's ratio ($\nu$) were examined. Properties obtained from a previous experimental setup [1] were also implemented; finite element results using these properties were then compared to the experimental data.

## RESULTS

The deformation of the cartilage layer demonstrated the expected creep pattern, increasing with time to an equilibrium plateau (when given sufficient time) under the constant aspiration pressure. A complex deformation profile in the cartilage layer was found during this creep (Figure 1). Because of the rigid boundary condition set at the cartilage-bone interface, the deflection was lower at the axis of symmetry than at the inside edge of the aspirator.

To assess the behavior of different types of cartilage, several analyses were performed, each assigned different material properties. Surface deflection (axial deformation) of the cartilage layer at the axis of symmetry, or center of aspiration, is reflected in these graphs (Figures 2-7). The expected creep phenomenon under the application of the aspiration pressure and during recovery is readily apparent. Properties representative of cartilage in compression, normal (Figure 2) and repair (Figure 3), were first evaluated. The repair cartilage deformed more than normal tissue but had similar creep profiles. The effect of an increased Poisson's ratio for normal tissue (Figure 4) was to decrease the surface deflection because of the greater resistance of the tissue to lateral deformation. With the small values of permeability used (typical of cartilage in compression), an equilibrium plateau was generally not reached in the 30sec time interval.

Comparison between finite element predictions and experimental behavior for one data set was performed. First, the compressive properties of the cartilage subjected to the aspiration pressure were determined from indentation testing [1]. These properties were then implemented into the finite element model (Figure 5). Experimental data however demonstrated significantly greater surface deflection (Figure 6). The experimental creep data under aspiration was then itself curve-fit to provide cartilage properties [6] in this different mode of loading. These properties were then implemented into the finite element model (Figure 7). The permeability was found to be quite high in comparison to cartilage in compressive modes of loading such that equilibrium was obtained in the 30sec interval of aspiration pressure. The finite element prediction however overestimated the creep response in comparison to experimental data.

Finally, after 30sec of applying the aspiration pressure, the pressure was released for analyses with each set of properties. Some residual deformation remained after 30sec of recovery, ranging from 36-42% for all finite element analyses except for the large permeability (Figure 7). If allowed sufficient time for recovery, the residual deformation becomes zero.

## DISCUSSION

This new nondestructive testing methodology was designed and implemented to provide characteristics of articular surfaces in a different testing configuration. The finite element analyses provided a way to depict cartilage behavior in this testing configuration.

The greatest amount of surface deflection, found using properties obtained from curve-fits of the experimental data, resulted largely from the high permeability. This allowed more deformation to occur during the 30sec interval. Differences existing between the finite element and experimental data are believed to be due to two reasons: 1) Obtaining properties from experimental data with a theoretical model that may not be appropriate, 2) Modeling cartilage as an isotropic material. Further refinements are necessary. Current studies are underway to combine new theoretical descriptions of cartilage in this testing configuration and extract tensile material properties of the cartilage layer. Additionally, further models are being developed to incorporate transverse isotropy in the solid phase behavior to provide more in depth information of cartilage behavior under aspiration.

## REFERENCES


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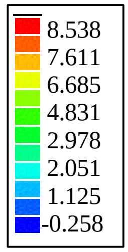
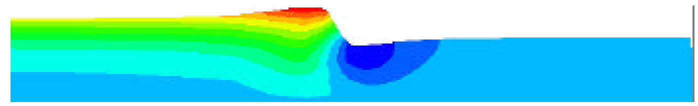



**Figure 1. Representative axial deformation (mm x10$^{-2}$) at completion of the first 30sec interval, scaled by a magnitude of 3 for visibility.**



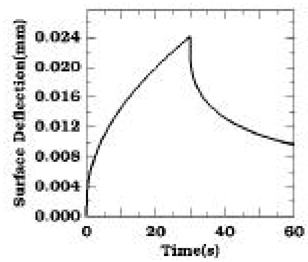



**Figure 2. Ha=0.7 MPa; k= 1x10$^{-15}$ m$^4$/N-s; $\upsilon$=0**

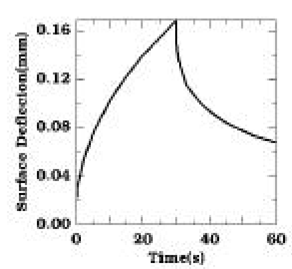



**Figure 3. Ha=0.1 MPa; k=7x10$^{-15}$ m$^4$/N-s; $\upsilon$=0**

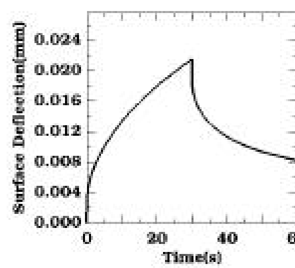



**Figure 4. Ha=0.7MPa; k=1x10$^{-15}$ m$^4$/N-s; $\upsilon$=0.3**

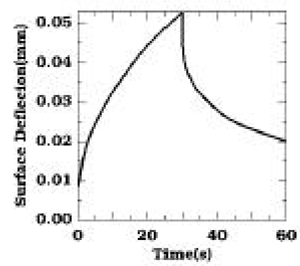



**Figure 5. Ha=0.2 MPa; k=1.39x10$^{-15}$ m$^4$/N-s; $\upsilon$=0**

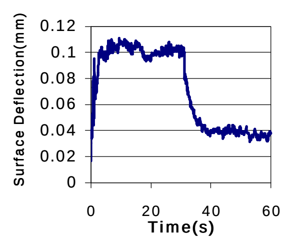



**Figure 6. Experimental cartilage deflection during aspiration trial**

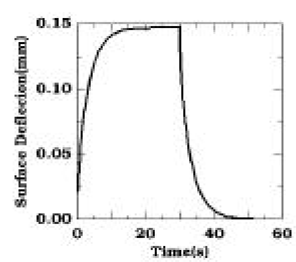



**Figure 7. Ha=0.4 MPa; k=1.06x10$^{-13}$ m$^4$/N-s; $\upsilon$=0**