

# FE ANALYSIS OF THE MECHANICAL BEHAVIOR OF CHONDROCYTES

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## INTRODUCTION

Chondrocytes are the living cells in articular cartilage (AC). They synthesize and maintain the extracellular matrix. Their activity is regulated by the interplay of genetic and environmental factors, such as soluble mediators, extracellular matrix composition, and mechanical factors. The mechanical environment of the chondrocytes has a significant influence on the health of the joint. In past studies of the mechanical behavior of chondrocytes (Wu and Herzog, 2000; Guilak and Mow, 2000), articular cartilage was described as a biphasic material consisting of a homogeneous, isotropic, linearly elastic solid phase, and an inviscid fluid phase, although AC is known to be highly anisotropic and inhomogeneous. In this study, AC is modeled by using the microstructure-based transversely isotropic, transversely homogeneous (TITH) model proposed by Federico et al. (2003, 2004). The purpose of this study was to analyze the mechanical behavior of chondrocytes as a function of location within the tissue, and to compare the predictions of classical isotropic, homogeneous (IH) models with those obtained using the TITH model.

## METHODS

In order to model chondrocyte deformation, we used a multi-scale step method (e.g., Wu and Herzog, 2000; Guilak and Mow, 2000), consisting of a macro-scale and micro-scale description for the entire tissue and the cells, respectively. At the macro-scale level, articular cartilage was assumed to be biphasic, and the elastic solid phase was modeled by use of the TITH model, i.e., as a

composite made of a proteoglycan matrix, a cell inclusion phase, and a depth-dependent, statistically oriented collagen fiber phase. The fluid phase was assumed to be inviscid and incompressible, with a deformation-dependent permeability (Holmes and Mow, 1990). All material properties for the TITH model were taken from the published literature. Cells were assumed to be axisymmetric ellipsoids and their aspect ratio  $\mathbf{a} = a/b$  ( $a$  and  $b$  being the vertical and the transverse semi-axes, respectively) and volumetric concentration depended on their depth location within the cartilage.

Chondrocytes are typically flattened ( $\mathbf{a} < 1$ ) in the superficial zone, spherical ( $\mathbf{a} = 1$ ) in the middle zone, and elongated ( $\mathbf{a} > 1$ ) in the deep zone (Clark et al., 2003). At the micro-scale level, a single cell was embedded in a cylinder with the same aspect ratio as the cell. The cylinder was made up of extracellular matrix (proteoglycan matrix plus collagen fibers). The homogenized elastic properties of the matrix were obtained by applying the TITH model to the proteoglycan matrix and fibers alone. The volume of the cylinder was given by the ratio of the cell volume (which was assumed constant in the initial unloaded state) and the cell volumetric concentration. The displacement and fluid pressure fields calculated at the macro-scale level were used as the time-dependent boundary conditions for the micro-scale model. In order to compare the TITH model with the IH model, the elastic constants for the IH model were taken to be equal to the average properties of the TITH model. Numerical simulations were made by means of the commercially available software ABAQUS

v6.3, and in accordance with experimental configurations (Guilak, 1995). The cartilage specimen was assumed cylindrical, 1.0mm thick, and had a diameter of 6.0mm. The specimen was subjected to a 15% unconfined compression load, at a constant rate during a ramp period of 30 s, and the deformation was then kept constant until 1200 s. Three chondrocyte locations were chosen for analysis. The locations of these chondrocytes were on the axis of symmetry ( $z$ -axis) which runs from the bone-cartilage interface to the articular surface: superficial ( $z = 0.9, a = 1/3$ ), middle ( $z = 0.5, a = 1$ ), and deep zone ( $z = 0.1, a = 3/2$ ).

## RESULTS AND DISCUSSION

In the superficial and middle zone, the normalized cell height predicted by the TITH model was significantly smaller than that predicted by the IH model throughout the loading and recovery phase (Fig. 1). The percentage decrease in cell height in the middle zone predicted by the TITH model was 14.5%, a value that compares well with the experimental value ( $14.7 \pm 6.4\%$ ) found by Guilak (1995). The TITH model predicted a smaller normalized cell volume, compared to the IH model, at all locations (Fig. 2). In particular, in the middle zone, the TITH model predicts a small volume decrease during the loading phase, and a short-term increase, followed by a decrease, in the recovery phase, whereas the IH model

predicts a monotonic decrease. We speculate that this difference is caused by the different fluid flows in the two models.

## SUMMARY

The results of this study indicate that anisotropy and inhomogeneity of AC dramatically influence the mechanical properties of the tissue on the macro- and microscopic level. We believe that studies at the micro- and macro-scale level will provide new insight into understanding the relationship between mechanical loading of AC and adaptive and degenerative biological responses controlled by the chondrocytes.

## REFERENCES

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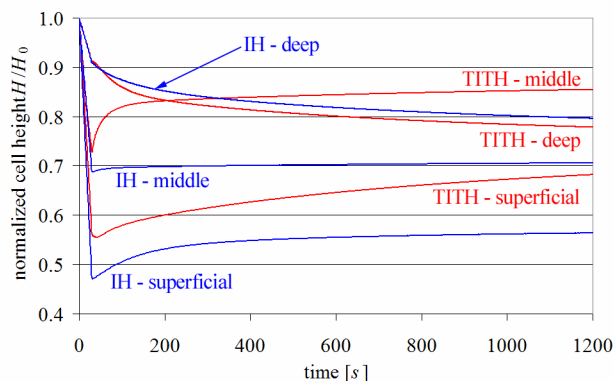


Figure 1. Normalized cell height

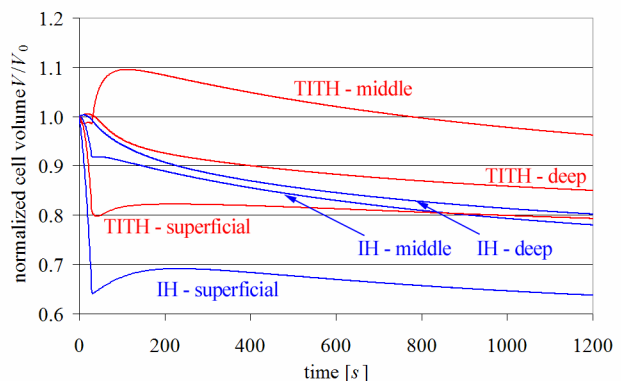


Figure 2. Normalized cell volume