VISCOUS EFFECTS MAY REGULATE ENDOCHONDRAL OSSIFICATION PATTERNS

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INTRODUCTION

- Mechanical load history plays a crucial role in the development and maintenance of the skeletal system [1,2].
- The influence of the mechanical environment on ossification patterns has been quantified in terms of the Osteogenic Index (OI) [2,3].
- OI is defined as a weighted sum of deviatoric (J_2) and hydrostatic (p) stress invariants [3]

$$\mathrm{OI} = \sqrt{\frac{2}{3}J_2} + kp$$

where k is a constant.

- The determination of the stress, and thus the OI, depends on the constitutive model. To date, all researchers have calculated the OI using an elastic material, except for [4], who used a biphasic material. Elastic material models do not account for the inherent viscous behavior of cartilage.

OBJECTIVES

- Develop a viscoelastic constitutive model of cartilage to simulate a diarthrodial joint during endochondral ossification.
- Determine if the viscous behavior of cartilage has a significant effect on the OI.
- **Hypothesis:** The size of the secondary ossific nucleus and thickness of the articular cartilage depend on the viscous properties of cartilage.

METHODS

- **Physiological Model:** A human humeroradial joint undergoing endochondral ossification is modelled with a plane strain finite element mesh (see Fig. 1).
- **Material Model:**
  Three-term constitutive model where E and ν are the elastic modulus and Poisson ratio, and η is the viscous damping parameter.

  Motivated by Kelvin-Voigt phenomenological models, where the elastic and viscous contriubtions are additive, write the stress response function S as

$$S = \underbrace{\frac{\nu E(\sqrt{\det C}-1)}{(1+\nu)(1-2\nu)}C^{-1} + \frac{E(C-1)}{2(1+\nu)}}_{S^{elas}} + \underbrace{\eta\dot{C}}_{S^{visc}}$$

  Set E= 2.04 MPa, ν = 0.47 [3], and examine the OI subject to a paramterization of η = [0, 2.04, 20.4, 200.4] MPa-s, where η = 0 corresponds to the purely elastic case.

- **Boundary Conditions:** Apply a load distribution F over the joint surface as shown in Fig 1. Scale the compressive loads from zero to full magnitude in a sinusoidal manner for four cycles at a frequency of 1 Hz. The OI is computed ten times per cycle for all four cycles.

RESULTS AND DISCUSSION

- **Effect on OI:** Figure 2 shows the OI, averaged over all four loading cycles, as a function of the viscous damping parameter. For purposes of comparison, the scaling threshholds are set so that the purely elastic case corresponds to results published in [3]. Increasing the damping causes an increase in the osteogenic index. This causes the appearance of a larger secondary ossific nucleus and a thinning of the articular cartilage layer.
- **Ossification Trend:** As the rudiment becomes more viscous, the OI increases, causing the secondary ossific nucleus to expand. This trend suggests that the viscous properties of cartilage may be important in the modulation of the endochrondral ossification process and in the determination of the articular cartilage thickness.

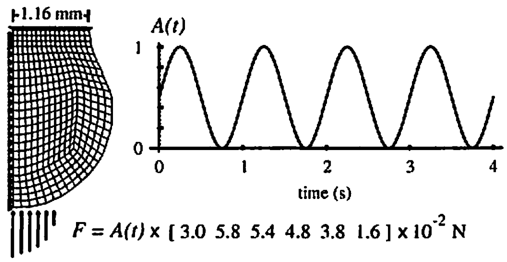
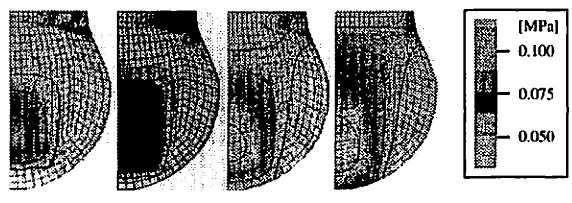


FIGURE 1: Finite element mesh with cyclic load distribution.



η : 0.0 MPa-s 2.04 MPa-s 20.4 MPa-s 200.4 MPa-s

FIGURE 2: Osteogenic Index (OI) averaged over four load cycles for varying values of the viscous damping parameter.

- **Future Work:** Dynamic physiological loading conditions often occur around 1 Hz, the value used in this study. The effects of loading frequency, another important variable, could be addressed in future work.

References: [1] J. Wolff, *The Law of Bone Remodelling*, 1892. [2] D.R. Carter, *J. Biomech.*, 20, p1095, 1987. [3] D.R. Carter and M. Wong, *J. Orthop. Rsh.*, 6, p804, 1988. [4] P.J. Prendergast and R. Huiskes, *Mech. of Comp. Matl.*, 32, p144, 1996.

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VISCOUS EFFECTS MAY REGULATE OSSIFICATION PATTERNS DURING JOINT FORMATION

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INTRODUCTION: The process of endochondral ossification has been hypothesized to be regulated by mechanical stress [1]. The propensity of cartilage to differentiate into bone is commonly captured by an osteogenic index (OI), defined in terms of stress invariants. The stress distribution, and thus the OI, depend on the underlying constitutive model. Many existing models assume cartilage to be a purely elastic material. Because such models do not account for the viscous solid-fluid interaction in the matrix, biphasic models have been developed based on the material microstructure of cartilage [2].

Most studies examining OI consider cartilage as an elastic material; few of them have considered the OI with a viscous material [3]. The objective of this study was to understand the role of viscous effects on the osteogenic index.

METHODS: We considered a diarthrodial joint undergoing endochondral ossification using a plane strain finite element model. While holding the distal end, we imposed a cyclic traction to the proximal end, causing compression at a frequency of 1 Hz for ten cycles.

We used a Kelvin-Voigt model for the cartilage (E=0.348 MPa, ν=0.34) [4] to provide a response similar to a biphasic model under confined compression. We then examined the OI as a parameter of the viscous damping η over the range [0, 0.05, 0.50, 5.00] MPa sec.

RESULTS: Fig. 1 shows values of the OI for increasing values of the viscous damping parameter η. Increasing the damping causes an increase in the osteogenic index corresponding to a larger radius of the secondary ossific nucleus and a thinning of the articlular cartilage. Decreasing the damping parameter to zero recovers the purely elastic case.

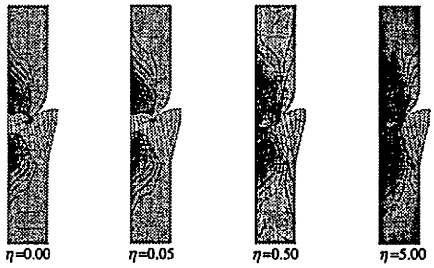

Figure 1. OI parameterized by viscous damping parameter η.

DISCUSSION AND CONCLUSION: We assumed that the viscous behavior of cartilage may play an important role in regulating the endochondral ossification process. We therefore developed a fully nonlinear, objective, phenomenological material model capable of capturing the response of a biphasic model. With the damping parameter η, we could modulate the size of the secondary ossific nucleus and therefore the thickness of the articular cartilage layer.

Dynamic physiological loading conditions typically have an upper bound of 1 Hz, the value used in this study. The effects of loading frequency, another important parameter, needs to be addressed in future work.

REFERENCES

1. Carter, J. Biomech., 20, 1095. **2**. Mow et al., Biomech. Of Diarth. Joints, Springer, 1990. **3**. Prendergast et al., Mech. Of Comp. Matl., 32, 144. **4**. Suh et al., J. Biomech., 28, 357.

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