POROELASTIC FINITE ELEMENT ANALYSIS OF A STEP-OFF ARTICULAR INCONGRUITY

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INTRODUCTION

One of the goals of intraarticular fracture repair is the prevention of post-traumatic arthritis by avoiding mechanical environments that increase the stresses in cartilage. A previous study has shown that contact pressures in the ankle increase significantly under quasi-physiological loading in the presence of an articular incongruity (step-off) [1]. Of particular interest from that study are the results from cadaveric tests in which the talus subluxated from the beneath the tibia. This motion created large transient stress on the displaced fragment. This study investigates the biphasic response of cartilage to such stress gradients. Corresponding contact stress transients are applied to a poroelastic finite element model to further elucidate the influence of a step-off on the stress distribution throughout the cartilage depth.

METHODS

A sagittal cross-section of tibial cartilage was modeled as a two-dimensional, plane-strain layer as shown in Figure 1. The shape of the tibia was taken from a Sawbones® model of a tibia and the cartilage was created by extruding the tibial profile 1.5mm downward (in the '-2' direction as shown in Figure 1).

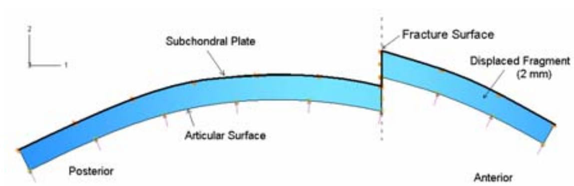
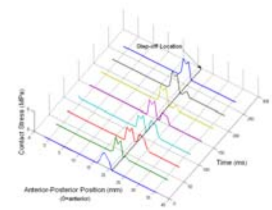


Figure 1. Tibia cartilage represented by a plane-strain model.

A transversely-isotropic, poroelastic material model was developed for this study using the ABAQUS finite element software (ABAQUS, Inc., Providence, RI). Material properties were derived from various published mechanical tests of articular cartilage. The out-of-plane and transverse moduli of elasticity were 0.45 MPa and 35 MPa, respectively [2],[3]. The Poisson's ratio characterizing the transverse response to a transverse load was 0.146 [4] and the Poisson's ratio characterizing the transverse response to an out-of-plane load was 0.074 [5]. Values for the out-of-viewing-plane shear modulus (G_{12} in the coordinate system of Figure 1) range from 0.5 to 4 MPa in literature [6]. However, these values are measured in the superficial or middle zones and the dominant shearing action in this model occurs at the cartilage subchondral plate interface. Since the deep layer of cartilage generally has a compressive stiffness about twice that of the superficial layer, a shear modulus of 10 MPa was used for this analysis. The permeability used was 1.14×10^{-15} $m^4/(N\text{-}s)$ [5]. The remaining material properties were determined according to the relationships governing transversely isotropic material. For cylinders in unconfined compression, the material model has been shown to exhibit the same characteristics (rate-dependent stiffness and hysteresis) as mechanical tests have shown.

For this analysis, the cartilage was considered fixed at the bone-cartilage interface. The step-offs were created by translating the anterior third of the cartilage proximally. Transient contact pressures from the fore-mentioned study were applied on the articulating surface as time-varying distributed surface loads as shown in Figure 2. The cartilage was meshed using 4-node poroelastic elements as shown in Figure 3.



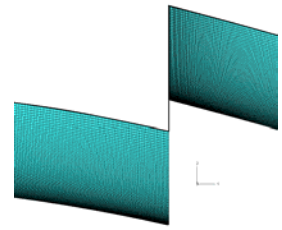


Figure 2. Contact pressures. **Figure 3.**Mesh at fracture surface.

RESULTS AND DISCUSSION

Typical Von Mises stress and pore pressure distributions are shown in Figures 4 and 5, respectively.

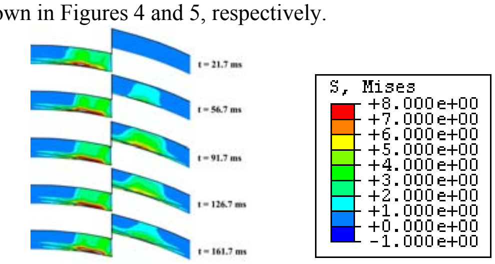


Figure 4. Von Mises stress in tibia cartilage with 2mm step-off.

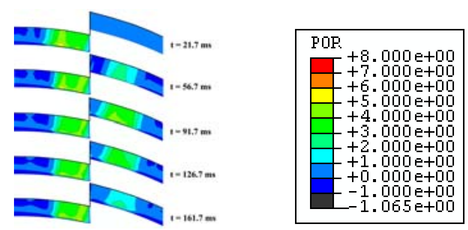


Figure 5. Pore pressure in tibia cartilage with 2mm step-off.

The fluid phase of the cartilage appears to play an important role in these simulations, particularly in the deep layers. Presumably due to the abrupt transient of contact stress on the displaced fragment during subluxation, deep layer fluid (pore) pressures there exceed solid-phase stresses. The fluid phase carries approximately 4 MPa, while the solid matrix phase carries 2 to 3.5 MPa. By contrast, the solid-matrix stress dominates in the superficial layers. This formulation provides a vehicle by means of which temporal and spatial anomalies of cartilage stress can be quantified for the situation of joint instability due to a surface incongruity. Such a transient "shuck" situation is strongly pre-disposed to post-traumatic osteoarthritis, for reasons presently not well-understood.

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