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Changes in articular cartilage mechanics with meniscectomy: A novel image-based modeling approach and comparison to patterns of OA

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ABSTRACT

Meniscectomy is a significant risk factor for osteoarthritis, involving altered cell synthesis, central fibrillation, and peripheral osteophyte formation. Though changes in articular cartilage contact pressure are known, changes in tissue-level mechanical parameters within articular cartilage are not well understood. Recent imaging research has revealed the effects of meniscectomy on the time-dependent deformation of physiologically loaded articular cartilage. To determine tissue-level cartilage mechanics that underlie observed deformation, a novel finite element modeling approach using imaging data and a contacting indenter boundary condition was developed. The indenter method reproduces observed articular surface deformation and avoids assumptions about tangential stretching. Comparison of results from an indenter model with a traditional femur–tibia model verified the method, giving errors in displacement, solid and fluid stress, and strain below 1% (RMS) and 7% (max.) of the absolute maximum of the parameters of interest. Indenter finite element models using real joint image data showed increased fluid pressure, fluid exudation, loss of fluid load support, and increased tensile strains centrally on the tibial condyle after meniscectomy—patterns corresponding to clinical observations of cartilage matrix damage and fibrillation. Peripherally there was decreased consolidation, which corresponds to reduced contact and fluid pressure in this analysis. Clinically, these areas have exhibited advance of the subchondral growth front, biological destruction of the cartilage matrix, cartilage thinning, and eventual replacement of the cartilage via endochondral ossification. Characterizing the changes in cartilage mechanics with meniscectomy and correspondence with observed tissue-level effects may help elucidate the etiology of joint-level degradation seen in osteoarthritis.

1. Introduction

Meniscectomy is a risk factor for knee osteoarthritis in humans as well as in animal models (Cox et al., 1975; Englund et al., 2001; Fauno and Nielsen, 1992; Ghosh et al., 1990; Huang et al., 2003; Jackson, 1968; Oakley et al., 2004). Animal studies of meniscectomy-induced osteoarthritis have demonstrated biological, biochemical, and biomechanical degradation of knee articular cartilage centrally, while peripherally, osteophytes develop (Appleyard et al., 2003, 1999; Oakley et al., 2004; Young et al., 2005, 2006).

Though meniscectomy-induced osteoarthritis is believed to be mechanical in etiology, various technical barriers have impeded progress towards understanding the mechanical stimulus initiating these osteoarthritic changes. To understand meniscectomy-induced osteoarthritis at the tissue-level, one must have the proper imaging and mechanical modeling tools to define the changing mechanical state of articular cartilage in the whole joint after meniscectomy.

It is now possible to measure the deformation of articular cartilage in a whole knee joint that is physiologically loaded. Song et al. (2008) investigated how meniscectomy alters time-dependent deformation of physiologically loaded articular cartilage in ovine knee joints using MRI. With this novel technique, they were able to quantify time-dependent articular cartilage nominal strain.

To examine the resulting cartilage tensor stresses and strains, a numerical study is needed to fully utilize the experimental data of Song et al. (2008). Mechanical modeling of articular cartilage in joints has traditionally been done by modeling the whole joint. (Donahue et al., 2002; Pena et al., 2006, 2005; Wilson et al., 2003).

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