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Stress distributions and material properties determined in articular cartilage from MRI-based finite strains

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ABSTRACT

The noninvasive measurement of finite strains in biomaterials and tissues by magnetic resonance imaging (MRI) enables mathematical estimates of stress distributions and material properties. Such methods allow for non-contact and patient-specific modeling in a manner not possible with traditional mechanical testing or finite element techniques. Here, we employed three constitutive (i.e. linear Hookean, and nonlinear Neo-Hookean and Mooney–Rivlin) relations with known loading conditions and MRI-based finite strains to estimate stress patterns and material properties in the articular cartilage of tibiofemoral joints. Displacement-encoded MRI was used to determine two-dimensional finite strains in juvenile porcine joints, and an iterative technique estimated stress distributions and material properties with defined constitutive relations. Stress distributions were consistent across all relations, although the stress magnitudes varied. Material properties for femoral and tibial cartilage were found to be consistent with those reported in literature. Further, the stress estimates from Hookean and Neo-Hookean, but not Mooney-Rivlin, relations agreed with finite element-based simulations. A nonlinear Neo-Hookean relation provided the most appropriate model for the characterization of complex and spatially dependent stresses using two-dimensional MRI-based finite strain. These results demonstrate the feasibility of a new and computationally efficient technique incorporating MRI-based deformation with mathematical modeling to non-invasively evaluate the mechanical behavior of biological tissues and materials.

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1. Introduction

Characterization of stress and strain patterns in load-bearing tissues such as articular cartilage is key to functionally evaluate the progression of tissue degeneration and treatment strategies for osteoarthritis, a disease affecting 27 million people in the United States (Lawrence et al., 2008). Moreover, knowledge of the structure–function relationships in cartilage provides a more comprehensive understanding of tissue integrity during degeneration and repair. By characterizing the properties of articular joint tissues and stress fields arising from applied loads, it may be further possible to predict failure or identify early markers of disease long before the joint otherwise shows signs of deterioration or declines in performance (Ea et al., 2011; Shirazi and Shirazi-Adl, 2009).

Articular cartilage is a complex material with behavior dominated by the interactions of cross-linked collagen networks, proteoglycans, and interstitial fluid (Mow et al., 1992). Characterizing the mechanical properties of the composite formed by these constituents *in situ*, however, is a difficult task. Cartilage deformations may be determined non-invasively by displacement-encoded magnetic resonance imaging (MRI;Chan et al., 2009b; Neu and Walton, 2008). Displacement-encoding with stimulated echoes (DENSE) and a fast spin echo (FSE) acquisition (Neu and Walton, 2008) has been used to determine *in situ* displacements and strains in tibiofemoral joints (Chan et al., 2009b). Based on measured strain fields in cartilage, stress patterns and intrinsic properties may be determined through further computational analysis.

MRI has been used to obtain joint geometry for use in finite element or mathematical analyses of the loading response, providing a patient-specific representation of the anatomy (Fitzpatrick et al., 2010; Gíslason et al., 2010; Pillai et al., 2007). A variety of constitutive models may be used in such modeling of joint mechanics. A linear elastic model, for example, provides a simple and straightforward relation between stress, strain, and material properties. Nonlinear models, in contrast, are more complex, yet far more descriptive of biomaterial behavior, including cartilage (Federico and Herzog, 2008; Galle et al., 2007). However, while

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