Spatial and depth dependent viscoelastic behavior of articular cartilage

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ABSTRACT

The mechanical response of the soft tissues of the knee is nonlinear, anisotropic, and viscoelastic. Individual tissues may also express nontrivial gradients of material properties throughout their structure, adding to the modeling complexity of the anatomy. Computational models of whole knee biomechanics can be extremely useful in understanding the progression of degenerative diseases and traumatic injury, such as osteoarthritis and anterior cruciate ligament (ACL) deficient knees, by examining localized tissue deformations in healthy and compromised knees. The accuracy of the biomechanical predictions generated by these computational models is predicated on the validity of the soft tissue constitutive relationships. Currently computational models of whole knee biomechanics contain material descriptions of the soft tissues that neglect one or more important characteristic biomechanics. What has been absent from current models is the necessary consideration to the intricate biomechanics of the tissues due to a lack of representative and reproducible experimental data and the ability to construct material descriptions that capture the relevant physiological response of soft tissues. This discussion will address current efforts in quantifying the mechanics of the tibial and femoral cartilage surfaces. We have shown that articular cartilage in the knee is characterized by a spatially heterogeneous, nonlinear mechanical response at a physiological strain rate by studying a population of healthy female cadaveric specimens in unconstrained compression. Based on our experimental data we developed a functionally graded constitutive relationship derived from an existing hyperelastic, anisotropic material model. We demonstrated that this modified model was capable of capturing the bulk response of the tibial and femoral cartilage surfaces with one spatially varied parameter, the initial stiffness. We incorporated the mechanically heterogeneous constitutive relationship into a finite element framework and examined the effect of heterogeneity on cartilage deformation in healthy, ACL deficient, and ACL reconstructed knees. Our computational investigation indicated that models which assume cartilage homogeneity underestimate compressive and in-plane shear strains and strain localizations during dynamic activities. The purpose of this study was to further refine our understanding of cartilage mechanics by examining the ability of our cartilage model to predict other simple deformation states experimentally and to investigate the extent of strain rate dependence during physiologically interesting activities, such as walking and traumatic injury. We also extended our computational investigation into understanding the effects of soft tissue material models on overall knee biomechanics. Our data suggest that cartilage tissue has significant strain rate dependence over the entire loading regime; however, nonlinear elastic behavior dominates its response during typical dynamic events. We have shown that, in addition to spatial mechanical heterogeneity, cartilage exhibits a depth-dependent, viscoelastic response. This dimension of mechanical heterogeneity is linked to the underlying macromolecular network, which varies in composition, density, and orientation. Including depth-dependent constitutive behavior increases the distribution of cartilage deformation and may provide insights into the initiation and progression of soft tissue injury and disease.