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A NEW CONTINUUM MODEL OF CARTILAGE ELASTICITY AND PERMEABILITY FACILITATES INSIGHTS ON STRUCTURE-FUNCTION RELATIONSHIPS

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Despite the extreme complexity of the fundamental mechanisms underlying cartilage function, computational modeling can bring biological and medical data together with physics and engineering science into a patient-specific simulation environment. To facilitate finite element analysis of this complex soft tissue, and hence further interdisciplinary studies, we generate a quasi-static, two-phase model with individually incompressible phases under isothermal conditions and without mass exchanges.

We model the proteoglycan solid as neo-Hookean, and define a compaction point as the state in which all transportable fluid is pressed out of the tissue. To model mechanical contributions from the collagen fiber network, we integrate the strain energies of single collagen fibers – weighted by an orientation distribution function (ODF) defined over a unit sphere – over the distributed fiber orientations in 3-D. We define the anisotropic intrinsic permeability of the cartilage solid matrix with a consistent spatial structural tensor based on the initial Darcy permeability, an isotropic deformation dependence and again the integration of the local ODF over all (normalized) spatial fiber orientations.

To increase the fidelity of our simulations, we define material parameters as constants, compositional parameters as functions of the normalized tissue thickness, and we use structural parameters to characterize local (element-wise) ODFs. We calibrate our model by fitting data from the cartilage mechanics literature and determine the element-wise ODFs directly from sample-specific Diffusion Tensor Magnetic Resonance Imaging (DT-

MRI) data. Recent publications report that the anisotropic diffusion of water in cartilage, as captured by DT-MRI, reflects the local ultrastructure of the collagen network [1]. We specifically develop our modeling formulation to accept structural data on the patient-specific collagen fiber network as determined via DT-MRI [2].

We implement our constitutive formulation in 3-D large strain finite elements and simulate mechanical indentation tests to study the distributions of interstitial fluid pressure, fluid pressure load support, and principal shear stress within the cartilage sample under indentation with a plane-ended, 1 mm diameter cylindrical indenter [3]. To determine the effects of the collagen fiber network and through-the-thickness tissue inhomogeneity (of tissue constituents) independently, we selectively simplify our model by removing either the fiber network, or the tissue inhomogeneity, or both.

Our simulations show the fiber network dramatically increases interstitial fluid pressure within the tissue and focuses it near the surface. Inhomogeneity of the constituents also increases fluid pressure (although less dramatically) and reduces principal shear stress in the tissue solid. Increased fluid pressure enhances load support, shields the solid matrix, promotes low frictional coefficients and thus reduces wear on the tissue. Additionally, a biphasic neo-Hookean model, as is available in commercial finite element codes, does not capture important features of the intra-tissue response, e.g. distributions of interstitial fluid pressure, principal shear stress and fluid pressure load support ratio.

High-fidelity, intra-tissue simulations allow us to consider complex problems in structure-function relationships, load support, contact and loading effects on cartilage degeneration, and provide insight to the mechanobiological cellular stimuli. Furthermore, 3-D finite element modeling of cartilage, calibrated using medical imaging modalities, has real potential to become a clinical diagnostic tool for patient-specific analysis.

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