Micromechanics Based Constitutive Relationships for Collagenous Tissue

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Structurally important components of soft tissues like the knee meniscus and articular cartilage are considered to be hydrated collagen fiber network, hydrated proteoglycan (PG) gel and free water. Consequently, we seek constitutive relationships of the type used for pressured fluid held in a porous, pre-tensed medium. Under physiological conditions, the fixed charged density of the proteoglycan gel creates an electrochemical potential difference between the tissue and the bath in which it is submerged. This potential difference creates an osmotic pressure in the fluid. Under no external load, the tissue is in a free swollen state with the tense fibrillar network resisting the osmotic pressure. Under external load, compressive stress is distributed between the fibrillar network, the interstitial fluid and to the PG gel. The overall stress in this poroelastic body is obtained from application of Signorini's theorem of stress means on the composite of the fibrillar network, interstitial fluid and non-fibrillar PG gel. The stress tensor of the continuous fibrillar network is derived using a surface integral involving all the fiber tractions in a spherical unit cell. Osmotic pressure in the interstitial fluid is calculated using a modified Donnan's model that concurs with data from existing literature. Stress on the non- fibrillar PG gel is estimated using a modified neo-Hookean model. The pre-tension under the initial free swollen condition is estimated using the equilibrium equation under zero external loads. Expressions for pre-strain in the collagen network under free swollen conditions have been obtained using the derived constitutive law for isotropic as well as anisotropic fiber network. Pre-strain magnitudes are critical in updating the constitutive relation consistent with the buckled microstructure of the fibrillar network. The constitutive relationship together with the pre-strain values is used to perform a parametric study of overall tissue behavior under uniaxial, drained loading conditions that are typically used in experimental testing. Current literature does not explain all mechanical phenomena observed during soft tissue loading using a single constitutive approach. The relationship developed using our microstructural modeling approach simultaneously explains confined and unconfined uniaxial behavior, variation in stress-strain behavior with microstructure, analysis of degenerated cartilage and variation in Poisson's ratio of the tissue material under compression. Stress-strain behavior under strain controlled uniaxial compression is found to be significantly affected by all the microstructural parameters such as fiber content, fiber stiffness, fiber anisotropy, fixed charge density and external bath concentration. The behavior under uniaxial compression can be delineated into linear, softening and hardening zones with different moduli. This is consistent with observations in the literature that indicate different linear and non-linear zones and varying moduli at different strain ranges during cartilage testing. For large pre-tension, the overall behavior can show softening at intermediate strain-levels. For small pre-tension and fiber stiffness, the overall behavior is dominated by the variation of osmotic pressure in the fluid. The decrease in Poisson's ratio with applied compressive strain is explained by the model with reference to successive buckling of fibers in the collagen network. All these phenomena follow naturally from the microstructural model without the need for any additional parameters apart from the mechanical properties of each of the constituents.