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TOWARDS AN ADVANCED POROVISCOELASTIC MODEL AT LARGE STRAINS FOR THE SIMULATION OF COLLAGEN INDUCED ANISOTROPY OF ARTICULAR CARTILAGE

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ABSTRACT

According to its function as a specialized type of low friction and wear-resistant connective material additionally distinguishing itself by exceptional load-bearing properties, articular cartilage tissue presents a complex hydrated composite structure. It consists of a porous, permeable and deformable solid skeleton which is completely filled out with a fluid component (interstitial fluid). Cartilage cells (chondrocytes) as a part of the solid matrix are embedded in the extracellular matrix (ECM) consisting primarily of a network of collagen fibers, and containing furthermore proteoglycans, glycoproteins and lipids. The solid constituents of the ECM are structurally charged on the molecular level. Hence, electrochemical potentials can build up with an additional influence on the mechanical behavior.

There is a huge number of publications dealing with the material behavior of hyaline articular cartilage, and its appropriate modeling (for an overview cf. [1]). As a rule, the tissue is modeled as a continuum consisting of one or more phases. Recently, more and more contributions can be found reporting the investigation and modeling of discrete structural elements (e.g. collagen) of the tissue as well as selected complex material effects (e.g. osmotic swelling).

The authors present a contribution to a more comprehensive realistic characterization and modeling of the complex biomechanical processes obtained in articular cartilage tissue under mechanical loading conditions. For the material modeling we propose a phenomenological macrostructural approach which describes microstructural effects by means of suitable constitutive equations. The thermodynamically consistent material model is based on a so-called overlay concept (cf. [2]). The basic idea of this superposition methodology is the additive decomposition of the stress tensor and the free Helmholtz energy

density respectively according to specific mechanical properties whose underlying physics can partly be illustrated on rheological models adapted to large strain conditions (see [3] and others).

We propose a biphasic model consisting of a solid phase and a fluid phase. Concerning the current state of the art it is generally recognized that articular cartilage is subjected to finite deformations. Furthermore, recent investigations have shown that due to the varying orientation of the collagen fibers the solid matrix of the cartilage tissue has to be considered as an anisotropic material characterized by tension-compression nonlinearities. The authors' attention is specially focused on those depth-dependent anisotropic phenomena associated with the specific features of the collagen network. Elastic anisotropy is characterized by structural tensors consistently defining appropriate polyconvex potentials.

Collagen fibers exhibit a triple-helical conformation of peptide chains. This macromolecular structure is responsible for stiffening effects of collagen at certain deformations. About one decade ago, Gent [4] proposed a material model to characterize strain hardening effects within the context of incompressible finite elasticity due to the limited chain extensibility of restricted elastic materials. Recently, this approach has been increasingly studied within the context of rubber elasticity as well as biomaterials like arterial walls (cf. [5,6]). Consequently, the authors adopted this idea to model stiffening effects of articular cartilage, and added a Gent-like term to the elastic part of the free Helmholtz energy density.

For a certain period the rate-dependency of a biphasic material behavior has exclusively been attributed to the fluid flow through the solid matrix. However, recent observations demonstrate that viscoelastic properties of the solid phase must not be neglected. Therefore, its intrinsic viscoelasticity is considered by appropriate constitutive relations based on the multiplicative decomposition of the deformation gradient into elastic and viscous parts (cf. [3]). Within this context, a special formulation of the viscous part of the free Helmholtz energy density characterizing transversly isotropic as well as Gent-like time-dependent material behavior is presented. The model is completed in a (quasi)static state by widely accepted approaches for the consideration of the pressure due to repulsive forces of the fixed charges presented in the ECM of articular cartilage.

The theoretical background and the numerical algorithms of all the parts of the material model under consideration are presented. This model has been implemented into a commercially available FE-code. Some numerical examples showing several structural effects are discussed within the context of experimental results.

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