Constitutive models for soft tissue considering length and directional statistics of the fibre bundles

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Abstract. The complex structure and composition of soft biological tissues gives rise to important challenges when modelling their macroscopic constitutive behaviour, due to their, most of the times, highly nonlinear and anisotropic stress-strain response as well as the large variability in their mechanical properties. These features are mainly due to the length as well as the spatial and directional random distributions of collagen and elastin fibres. To take all these effects into account, a fully three dimensional finite-strain-driven model for fibrous soft tissue is here presented that includes its inherent microstructural variability. This model has been developed under the framework of finite-strain hyperelasticity assuming uncoupled contributions for the matrix and fibres, and uncoupled bulk and deviatoric responses. A simple isotropic neo-Hookean-type law is used to model the deviatoric response of the ground substance, whereas a micro-structural approach is employed to model the contribution of fibres. An individual fibre is assumed to follow a worm-like elasticity model such as its length has been considered a random variable following a beta probability density function. The macroscopic hyperelastic response of the tissue is then derived and explicit expressions for the strain-energy function are given. Anisotropy is included by means of a directional distribution for the fibres at each representative volume element (von Mises and Bingham have been used), while the passage from micro-structural contributions to the macroscopic response is obtained by a computational homogenisation scheme, namely numerical integration over the surface of the sphere. The treatment of this integration is discussed in detail and several cubatures of the micro-sphere are tested to optimise the accuracy together with a reasonable computational cost. A simple isotropic damage mechanism within the framework of continuum damage mechanics is used to describe the softening behaviour under deformation for the matrix. On the other hand, fibres are uncrimped by increasing strain according to the specific fibre length distribution thus failing at different strain levels. Fibre failure is introduced by the weakest link principle, where the probability of failure for a given fibre is related to its length. Theoretical examples of uniaxial and biaxial tests of a soft tissue reinforced with two families of collagen fibres have been solved to demonstrate the capabilities of the proposed model. Material parameters are identified from simple tension tests on human coronary arterial tissue. Later on, an artery-like two-layered tube subjected to internal pressure is simulated. Results show that the model is able to capture the typical stress-strain behaviour observed in fibrous soft tissue and seems to confirm the soundness of the proposed formulation.