A model for the mechanical response with damage of collogenous biostructures

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Mechanics of soft collagenous tissues is highly influenced by its structured histological macroscopic organization as well as by a number of mechanisms occurring at both micro- and nano-scale. Collagenous tissues can be regarded as fiber reinforced composite materials where the reinforcement phase is represented by crimped collagenous fibers. Such fibers are bundles of densely packed fibrils, that is tilted structures made of staggered arrays of cross-linked tropocollagen molecules. Adjacent fibrils within a fiber are themselves stabilized by lateral fibril-to-fibril covalent cross-links. As experimental evidences and molecular models suggest, cross-links affect molecular rearrangement mechanisms (slippage and gap increasing) and, depending on their density, both yield and tensile strength of fibrils (Buehler, 2008).

Regular soft collagenous tissues (such as tendons, ligaments and aortic tissue) usually experience a non-linear J-shaped stress/strain response (Fratzl, 2008). A reversible nonlinearity source in tissue tensile tests is related to the transition from less ordered molecular states (molecular kinks) to more ordered ones, usually addressed as a source of entropic elasticity (Buehler and Wong, 2007). Moreover, nanoscale effects and cross-link density highly affect tissue failure in terms of both ultimate strength and failure mechanisms.

Multiscale techniques have been revealed to be effective and powerful for describing soft tissue mechanical response, allowing to take into account dominant effects related to very different physical scales. In present work, a piecewise continuous convex constitutive response for modelling at the nanoscale the transition from entropic towards energetic elasticity of collagen macromolecules is employed. Moreover, both the molecular damage at the nanoscale and the fibrils damage at the microscale are modelled by assuming an unilateral behaviour of both molecules and cross-links, respectively. Employing standard tools deriving from convex analysis, that is by introducing suitable dissipative pseudo-potentials, a brittle failure is reproduced for molecules, whereas a ductile irreversible response is accounted for cross-links. By using a two-step nano-micro-macro homogenization technique (Maceri et al., 2010), this approach allow to model the experimental behaviour at the macroscale of soft collagenous tissues, starting only from few parameters measurable by simple histological tests. A number of benchmarks is proposed, showing the effectiveness and the accuracy of present model, as well as its capability to analyze the influence of collagen-related genetic defects.

References

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