Mechanics of intervertebral disc annulus: importance of osmo-inelastic coupling and structural features

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As the main soft component of the spine, the annulus fibrosus of the intervertebral disc is probably the most extraordinary tissue that the nature produces, mainly for its unusual time-dependent properties strongly influenced by the biochemical environment and the mechanical loading. A constitutive representation of the mechanics of the intervertebral disc annulus that considers as well regional effect, chemical sensitivity and time-dependency has not yet been developed, and it is hence the aim of the present contribution. In (Derrouiche et al., Biomechanics and Modeling in Mechanobiology, 2019; Kandil et al., Acta Biomaterialia, 2019), a physically-based model is proposed by introducing a free energy function that takes into account the actual disc annulus structure in relation with the surrounding biochemical environment. The response is assumed to be dominated by the viscoelastic contribution of the extracellular matrix, the elastic contribution of the oriented collagen fibers and the osmo-induced volumetric contribution of the internal fluid content variation. The regional dependence of the disc annulus response due to variation in fibers content/orientation allows a micromechanical treatment of the soft tissue. A finite element model of the annulus specimen is designed while taking into consideration the ‘interlamellar’ ground substance zone between lamellae of the layered soft tissue. The kinetics is designed using full-field strain measurements performed under different osmotic conditions and two disc annulus regions. The time-dependency of the tissue response is reported on stress-free volumetric changes, on hysteretic stress and transversal strains during quasi-static stretching at different strain-rates and on their temporal changes during an interrupted stretching. Considering the effective contributions of the internal fluid transfer and the extracellular matrix viscosity, the microstructure-based chemo-mechanical model is found able to successfully reproduce the significant features of the macro-response and the unusual transversal behavior including the strong regional dependency from inner to outer parts of the disc: Poisson’s ratio lesser than 0 (auxetic) in lamellae plane, higher than 0.5 in fibers plane, and their temporal changes towards usual values (between 0 and 0.5) at chemo-mechanical equilibrium. The underlying time-dependent mechanisms occurring in the tissue are analyzed via the local numerical fields and important insights about the effective role of the interlamellar zone are revealed for the different disc localizations. Although the annulus stretching is representative of the compression mechanics of intervertebral disc, the capabilities of the constitutive model to predict other mechanical loading paths are shown. A finite element model of a functional spine unit ‘vertebra-disc-vertebra’ is proposed using our constitutive framework and illustrative scenarios under different spine movements are shown with the aim of analyzing the local numerical fields and hence understanding the respective role of the different disc components.

References: