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A multiscale biphasic framework for fluid-microstructure interactions in biological tissues

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Abstract

The mechanical behavior of human soft tissues is strongly governed by the architecture and interactions of their biological polymer networks. Nowhere is this interplay more emblematic than in the intervertebral disc (IVD), where osmotic swelling of the proteoglycan-rich nucleus pulposus (NP) and tensile resistance of the collagen fiber network of the annulus fibrosus (AF) cooperate to regulate load sharing, fluid pressurization, and damping. Despite their intrinsic coupling under fluid-saturated conditions, these mechanisms are still commonly addressed in isolation in computational models. In this work, we propose a unified multiscale biphasic framework that explicitly captures fluid-microstructure interactions within a single continuum description of IVD mechanics. The model combines anisotropic fiber recruitment, osmotic swelling effects, and Darcy-type poro-mechanical fluid transport within a finite element formulation [1-3]. A dedicated multiscale identification strategy is introduced to independently calibrate each constitutive mechanism using experiments targeting NP pressurization, AF fiber kinematics, and fluid-driven responses. This separation of scales enables robust parameter identification while preserving nonlinear couplings when reintegrated at the organ level. The proposed framework reveals complex mechanical behaviors that cannot be reproduced by classical constitutive approaches, including auxetic-like transverse deformations and rate-dependent hysteresis arising from the competition between microstructural reorientation and fluid redistribution

[2]. Patient-specific geometries and degeneration-related material alterations were incorporated to investigate how changes in hydration, proteoglycan content, and fiber organization affect fluid transport and load transfer within the IVD [3]. Simulations under physiologically relevant loading scenarios - such as osmotic recovery, sustained compression, and multiaxial cyclic motions - demonstrate that the characteristic responses of healthy and degenerative IVDs emerge from nonlinear couplings between fluid flow and microstructural rearrangements. By bridging microstructural mechanics and organ-scale fluid transport, this modeling strategy provides a predictive tool for identifying mechanically vulnerable regions and assessing the impact of degeneration or therapeutic interventions. It also lays the foundation for future extensions incorporating biological processes such as nutrient transport and extracellular matrix turnover.

Keywords:

Intervertebral disc Fluid-structure interaction Time-dependent mechanics Multiscale mechanics Patient-specific variability

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