20th European Mechanics of Materials Conference - EMMC20
Florence, Italy | May 27th-29th, 2026
www.emmc20.unifi.it

Active Fluid-Solid Interaction in Tissue Invasion: Decoupling Indentation and Degradation Mechanics

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Paper ID: 560
Symposium S11: Mechanics of biological materials & biomechanics
Extended Abstract

Abstract

The penetration of active cellular tissues into the fibrous extracellular matrix (ECM) is a critical mechanical process driving biological phenomena ranging from embryonic morphogenesis to cancer metastasis. While the resulting engulfment morphologies often appear identical, they originate from fundamentally distinct driving mechanisms: mechanical indentation induced by active cellular tensions (elastocapillarity) versus biochemical degradation of the substrate. Disentangling these modes is crucial, as the mechanical state of the ECM dictates cellular fate through mechanotransduction. In this work, we present a rigorous continuum mechanical framework to investigate the competitive dynamics between these two modes. We model the cellular aggregate as a viscous active fluid droplet interacting with a hyperelastic solid substrate. The problem is formulated using a Nitsche-Onsager variational approach [Cicconofri et al. 2024], which naturally handles the energy dissipation and force balance at the fluid-solid interface. To address the computational challenges inherent in multi-phase flows with non-material moving boundaries, we employ a numerical framework utilizing non-conforming meshes and a phase-field description. We demonstrate the high predictive robustness of this approach through validation against analytical wetting theories and experimental data on elastocapillarity [Style et al. 2013] and human colon carcinoma (HCT-8) cell colonies

[Shi et al. 2022]. Leveraging this framework, we analyze the mechanical equilibrium of engulfing tissues, revealing a fundamental mechanosensing inhibition mechanism: substrate tension acts to negatively regulate the degradation rate. Furthermore, our relaxation simulations indicate that this interaction leaves a permanent \emph{invasive signature}, a residual deformation field that persists in the substrate even after tissue removal. This finding suggests that the history of the competition between active stress and matrix remodeling is mechanically encoded in the ECM.

Keywords:
Cell Invasion Cut FEM Elastocapillarity