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Research paper

A constrained mixture approach to mechano-sensing and force generation in contractile cells

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ABSTRACT

Biological tissues are very particular types of materials that have the ability to change their structure, properties and chemistry in response to external cues. Contractile cells, i.e. fibroblasts, are key players of tissue adaptivity as they are capable of reorganizing their surrounding extra-cellular matrix (ECM) by contracting and generating mechanical forces. This contractile behavior is attributed to the development of a stress-fiber (SF) network within the cell's cytoskeleton, a process that is known to be highly dependent of the nature of the mechanical environment (such as ECM stiffness or the presence of stress and strain). To describe these processes in a consistent manner, the present paper introduces a mutiphasic formulation (fluid/solid/solute mixture) that accounts for four major elements of cell contraction: cytoskeleton, cytosol, SF and actin monomers, as well as their interactions. The model represents the cross-talks between mechanics and chemistry through various means: (a) a mechano-sensitive formation and dissociation of an anisotropic SF network described by mass exchange between actin monomer and polymers, (b) a bio-mechanical model for SF contraction that captures the well-known length–tension and velocity–tension relation for muscles cells and (c) a convection/diffusion description for the transport of fluid and monomers within the cell. Numerical investigations show that the multiphasic model is able to capture the dependency of cell contraction on the stiffness of the mechanical environment and accurately describes the development of an oriented SF network observed in contracting fibroblasts.

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1. Introduction

Biological tissues are very particular types of materials that have the ability to change their structure, properties and chemistry in response to external cues. This fast response capability can be attributed to the out-of-equilibrium nature of the tissue structure, resulting from a constant cross-talk between a population of cells and their surrounding extra-cellular matrix (ECM). These interactions allow cells to sense stimuli conveyed by the ECM (Lambert et al., 1998) (such as force, deformation or flow) and the ECM to restructure due to the action of cells (characterized by traction forces Tamariz and Grinnell, 2002; Dallon and Ehrlich, 2008 or enzyme degradation Vernerey et al., in press). In this context, a large number of studies have demonstrated that cell contraction and architecture were strongly dependent on substrate stiffness (Wang et al., 2000; Solon et al., 2007; Guo et al., 2006; Levental et al., 2006), giving mechanics

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