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A power-law rheology-based finite element model for single cell deformation

E. H. Zhou · F. Xu · S. T. Quek · C. T. Lim

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Abstract Physical forces can elicit complex time- and space-dependent deformations in living cells. These deformations at the subcellular level are difficult to measure but can be estimated using computational approaches such as finite element (FE) simulation. Existing FE models predominantly treat cells as spring-dashpot viscoelastic materials, while broad experimental data are now lending support to the power-law rheology (PLR) model. Here, we developed a large deformation FE model that incorporated PLR and experimentally verified this model by performing micropipette aspiration on fibroblasts under various mechanical loadings. With a single set of rheological properties, this model recapitulated the diverse micropipette aspiration data obtained using three protocols and with a range of micropipette sizes. More intriguingly, our analysis revealed that decreased pipette size leads to increased pressure gradient, potentially explaining our previous counterintuitive finding that decreased pipette size leads to increased incidence of cell blebbing and injury. Taken together, our work leads to more accurate rheological interpretation of micropipette aspiration experiments than previous models and suggests pressure gradient as a potential determinant of cell injury.

Keywords Cell mechanics · Soft glassy rheology · Finite element analysis · Mechanotransduction · Cell injury

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E. H. Zhou (✉)
Program in Molecular and Integrative Physiological Sciences, Department of Environmental Health, Harvard School of Public Health, Boston, MA 02115, USA
e-mail: ezhou@hsph.harvard.edu

F. Xu
The Key Laboratory of Biomedical Information Engineering of Ministry of Education, School of Life Science and Technology, Xi'an Jiaotong University, 710049, Xi'an, People's Republic of China

F. Xu
Biomedical Engineering and Biomechanics Center, Xi'an Jiaotong University, 710049 Xi'an, People's Republic of China

S. T. Quek
Department of Civil Engineering, National University of Singapore, Singapore 119260, Singapore

C. T. Lim
Department of Bioengineering, National University of Singapore, Singapore 117576, Singapore

C. T. Lim
Department of Mechanical Engineering, National University of Singapore, Singapore 117576, Singapore

C. T. Lim
Mechanobiology Institute, National University of Singapore, Singapore 117411, Singapore

1 Introduction

Recent literature reveals an intimate interplay between biology and mechanics. For example, in diseases such as cancer, prominent alterations are often found to occur to the cellular mechanical properties (Guck et al. 2005; Cross et al. 2007; Jaalouk and Lammerding 2009). Accurate determination of these properties may therefore shed light on the health state of a cell as well as disease mechanisms (Suresh et al. 2005; Zhou et al. 2011). To this end, a variety of experimental techniques have been developed to deform the cell with controlled forces (Lim et al. 2006a; Bao and Suresh 2003). Nonetheless, despite the accurate measurement of these forces and deformation, intrinsic material properties remain difficult to quantify. The difficulty lies in the heterogeneity, active cyto-