Multiscale Techniques for Biomaterials

Dirk Hartmann, BIOMS, University of Heidelberg

Mechanical properties are a key feature in a wide rage of animal cell functions, including growth, motility, and gene expression. However, mechanical processes in living materials are fundamently different from common materials studied in material sciences. According to external or internal stimuli materials can evolve, e.g. intrinsic growth, or adapt, e.g. alter mechanical properties. Typical examples are growing cell cultures or formation of stress fibers in migrating keratocytes.

The main challenge for a theoretical treatment of mechanical processes in living materials is the derivation of appropriate constitutive relations, which need to take account of evolution and adaptation. Here, we present a rigorous multiscale approach for the derivation of appropriate macroscopic constitutive relations based on microscopic models.

Modeling mechanics of cytoskeletal networks or cell cultures often discrete microscopic models in terms of energy functionals are employed. However macroscopic continuum models are usually preferable from a computational point of view, since the required discretisation can be chosen appropriately and is not prescribed by the microscopic geometry. But finding such macroscopic descriptions is often a non-trivial task. Considering microscopic models given in terms of free energies Gamma-convergence is the ideal framework for rigorously bridging the gap between discrete microscopic and continuous macroscopic models.

Mechanics of red blood cells are considered as one test case to show how such a rigorous multiscale framework can be employed to derive appropriate macroscopic constitutive laws. Based on a well developed microscopic model a macroscopic model for the membrane bound cytoskeleton is rigorously derived. Coupled with a description of lipid bilayer mechanics, based on the Canham-Helfrich energy functional, an appropriate mechanical model for the membrane is developed. Considering additionally the Stokes Equation as a model for the cytosol a complete continuum mechanical description of the red blood cell is given. A quantitative comparison of optical tweezers experiments and corresponding simulations of the underlying microscopic model and simulations of the macroscopic continuum model (using FEM) underline the power of the proposed multiscale framework.

Further, we discuss the application of the multiscale framework to the derivation of appropriate macroscopic constitutive laws for growing cell cultures as well as for the formation of stress fibers in migrating cells. We believe that using similar approaches in many other biological systems macroscopic mechanical behavior and properties can be directly related to the vast knowledge on microscopic scales.