PREFACE

Mechanics in biology: cells and tissues

Biology is becoming the most important interdisciplinary field where physics and mathematics meet. The discoveries that have characterized biological sciences in the last few decades, and the insight made possible at the cellular and subcellular scales, offer fertile grounds on which to develop a formal description of biology using the quantitative methods of physics. One important goal in this effort is to understand the complex rules that govern living matter within the precise formal framework provided by the balance laws of mechanics.

Living organisms show the remarkable ability to change not only their geometry, but also their internal architecture and material properties in response to environmental changes. Mechanics is relevant to several aspects of biology, depending on the specific spatial scale size under consideration: the molecular scale (i.e. DNA transcription, protein folding and chemical cascades); the cellular scale (i.e. motility, aggregation, morphogenesis and mechanotransduction); the tissue scale (growth and remodelling); and the organ scale.

A compelling scientific topic is the mathematics of growth and remodelling of soft biological tissues. This topic, at the crossroads of biology, mathematics and continuum mechanics, concerns the statement and analysis of equations that characterize the mechanics, growth and remodelling of systems such as arteries, tumours and ligaments, studied at the macroscopic scale. These are ‘open continuous systems’, and they pose new challenging questions, which go beyond the standard mechanics that is traditionally devoted to closed systems.

The role of mechanics is even more crucial at a cellular level: what are the internal forces that generate cell deformation; how is cell traction transmitted to the environment; and what are the dynamics governing cell mechanotransduction? These are examples of the basic questions that leading research groups in the world are currently trying to address. While standard biology answers these questions in a descriptive, empirical manner, mechanics tries to provide a framework for quantitative prediction. The underlying equations often have to be re-expressed in a non-standard form; they usually involve multiple fields and are highly nonlinear. Special numerical methods are often needed, and the development of appropriate numerical tools has become an essential ingredient to successful research in this field.

The contributions collected in this Theme Issue of Philosophical Transactions A offer a state-of-the-art overview of current research in the field, with an emphasis on the different spatial scales that characterize it.

One contribution of 12 to a Theme Issue ‘Mechanics in biology: cells and tissues’.
The experiments of cell mechanics on arrays of micropillars, as the one illustrated by Patrick McGarry and co-workers, provide details of the dynamics pattern that was not even conceivable a few years ago. The effectiveness of the new experimental techniques poses mathematically challenging questions that span from simple lipid membranes (as in the work by Paolo Biscari and Gaetano Napoli) to the modelling of a whole cell system in its locomotion on a flat surface (as the fish keratocyte addressed by Hans Othmer and co-workers).

Morphogenesis of biological organisms has fascinated scientists for well over a century. In biology, differentiation is usually explained solely in terms of genetic expression; however, the newly emerging view is that the genetic code contains a limited amount of information, much less than the details exhibited by the astonishing richness of life. A possible explanation of this apparent conundrum could be that physical laws accompany gene expression, so that ordered spatial heterogeneity can be obtained on the basis of very simple mathematical rules. Therefore, much less information needs to be stored and transmitted, with an evident advantage in terms of energy expended and survivability. In this Theme Issue, Larry Taber discusses the state of the art of morphomechanics, a theoretical framework that has already been able to provide some theoretical explanations of emerging structures on the basis of a few basic principles. Embryonic development is the most promising field of morphomechanics, and here Pasquale Ciarletta, Martine Ben Amar and Michel Labouesse show how a continuum mechanics description of the stress field in the Caenorhabditis elegans embryo can predict its modifications in shape. Nonlinearity and instability are, of course, essential ingredients of the theory at the crossroads between mathematics and mechanics, as shown by Rebecca Vandiver and Alain Goriely.

Growth and remodelling of soft biological tissues have attracted increasing efforts and have produced a steady flow of quantitative results in the past few years. The complexity of the cardiac muscle is emerging as the new challenge in this respect. Gerhard Holzapfel and Ray Ogden review the morphology and structure of the myocardium and discuss the main features of the mechanical response of passive myocardial tissue. Fibres play a major mechanical role in biological tissues, and they are discussed in this issue in two papers: one experimental and the other theoretical. Jeff Ruberti and his group demonstrate that mechanical strain enhances the survivability of collagen micronetworks in the presence of collagenase. Andreas Menzel and Tobias Waffenschmidt propose a new remodelling approach that reflects the alignment of fibrous soft biological tissue with respect to representative loading directions, while based on a sound micro-mechanically motivated formulation.

Biological tissues are strongly heterogeneous systems, and the coexistence of several components at their microstructural scale suggests the use of mixture theories as a natural framework for their modelling. This issue contains two contributions in this respect. Stephen Cowin, Gaffar Gailani and Mohamed Benalla address interstitial flow in bone tissue on the basis of the theory of poroelastic materials with hierarchical pore space architecture. Arturo Valentin and Jay Humphrey reconsider the fundamental hypotheses that underly constrained mixture models of arterial growth and remodelling. Their findings emphasize the importance of formulating biologically motivated constitutive relations in any theory of growth and remodelling.
When we first broached the idea of a Theme Issue on ‘Mechanics in biology: cells and tissues’, we felt the need to collect the state of the art of this fascinating emerging subject. Now, when this issue is in the hands, or on the screens, of the readers, we feel that we have succeeded beyond our expectations. We thank the authors for their excellent contributions and the Publishing Editor Suzanne Abbott for her support and patience.

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