MECHANICS OF BIOLOGICAL AND BIOMIMETIC MATERIALS AT SMALL LENGTH-SCALES

This special issue of the Journal of Materials Research contains articles that were accepted in response to an invitation for manuscripts.

Introduction

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There has been recent rapid growth in research activity at the interface of materials science and biology. One exciting field at this interface is the topic of this focus issue: the study of the mechanical behavior of biological systems, or the way that naturally occurring materials respond to mechanical forces and deformations.

The study of biomechanics is not new. The pioneering work of "The Father of Biomechanics," Professor Y.C. Fung,[1–3] helped establish the field as an autonomous scientific discipline within the broader field of bioengineering. For many years, the discipline has included investigations at predominantly macroscopic length scales, including the description of whole-body motion, experiments on the mechanical responses of organs and tissues, and the development of continuum-based constitutive laws to describe tissue behavior.

Biological materials are not continuous media but are composites consisting of living components (cells) in a nonliving extracellular matrix (ECM) that is built and remodeled by the cells.[4] The ECM has functions that are inherently mechanical, providing a framework for holding and protecting cells. In addition, the ECM itself can be a composite material with multiple phases including any number of organic and inorganic constituents. The complexity of natural materials can be quite astonishing, with many levels of hierarchical structure over a range of length scales. Biological materials are dynamic; there exists great potential for changes in the tissue hierarchy with growth and development or with disease because of the action of live cells.

Due in part to the hierarchical organization of natural materials, the mechanical response can vary depending on the length-scale of observation. Most cells are 1–10 μm in size, but structural ECM components, including individual tropocollagen molecules and bone mineral platelets, are much smaller. Especially at fundamental length-scales, there is dramatic structural heterogeneity in natural materials due to distributions in shape, size, composition, and mechanical properties of the constituents. Interfacial effects may also play a large role in the local mechanical response. Thus, biological materials naturally fit within the scope of "nanomaterials," although organ-level components (e.g., a thigh bone) can be many orders of magnitude larger. Great scope therefore exists for experiments at both very small (nanometer) length-scales and multi-scale investigations incorporating higher levels of organization.

Recent advances in biology and medicine, including genomics[5] and proteomics,[6] have resulted in an increased interest in understanding biological systems at molecular (ECM) and cellular levels. This has been paralleled by a shift of focus in biomechanics to increasingly smaller length-scales. With this shift has come the application of materials science techniques, many developed for probing materials at the atomic and molecular scale, to the study of biological systems. The introduction of materials science techniques to the study of biomechanics has also been associated with the application of materials science philosophy to biological problems: focus has shifted subtly from purely mechanical explorations to

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investigations concerned with structure-property relationships. New and developing subspecialties have appeared, including multi-scale theoretical modeling of hierarchical biological structures, nanoindentation and nanotribology of biological materials, nanomechanics of individual biological constituents, single cell mechanics, and examination of bioadhesion and biolubrication.

Advances in understanding of both the structure and mechanical response of natural materials can directly influence the generation of engineered biomimetic materials. There exists great potential for mimicry in both biological applications (e.g., tissue replacement) and nonbiological applications (e.g., composites for space travel). Biomimesis also includes exciting developments involving novel materials processing techniques aimed at the generation of hierarchical and complicated structures.

This focus issue begins with a series of invited review articles examining the state of the art in three different fields of study. First, Suresh reviews the effects of a group of hereditary and infectious diseases on the structural and mechanical response of human red blood cells. In the process, a paradigm for the materials science of biology is presented: the relationship between structure, properties, and disease. In the second review, Ager, Balooch, and Ritchie present a comprehensive discussion of the fracture behavior of bone. Fundamental aspects of mechanism are explored in considering how bone fracture properties are altered in aging and disease. Finally, Angker and Swain examine the measurement of dental tissue properties by nanoindentation. In addition to basic structure-properties relationships for different tissue types, the implications for restorative dentistry are considered. In each of the three reviews, changes are found in the mechanical properties of biological materials with disease, demonstrating the potential utility of mechanical assays for diagnostic purposes.

The focus issue continues with contributed papers, in which a large number of different materials science techniques are used for mechanical characterization of a wide range of biological and biomimetic systems. The techniques used for characterization include (but are not limited to) indentation and nanoindentation, deformation by optical tweezers, scanning probe techniques, spectroscopy, electron microscopy, and both analytical modeling and computational modeling methods. The investigations presented here include the study of a wide variety of different mechanical properties, including elastic and plastic deformation, viscous flow, fracture, and adhesion. A range of material length-scales have been studied. These studies serve to demonstrate that mechanical responses can be highly sensitive to structural organization in natural and nature-mimicking materials. Subtle changes in structure due to disease or environmental changes can dramatically alter the behavior. Such studies not only reveal mechanical information about the materials but also enhance understanding of their biology and chemistry.

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