Foreword

Mechanical characterization and modeling of tissues and biomedical materials across different length scales

The title of this special issue follows that of a minisymposium being part of the European Congress and Exhibition on advanced Materials and Processes (EUROMAT2001) held in Montpellier - France, 12-15 September 2011, and several of the speakers invited to this minisymposium agreed on contributing to this issue, presenting recent work of theirs on the topic. The aim of the symposium was "*the fruitful interplay of experiments, theory, and computations across different length scales, when it comes to deciphering the origins of the intriguing mechanical behavior of hierarchically organized biological materials and structures.*".

Interdisciplinarity is a key characteristic of contemporary science, where thanks to more and more ubiquitiously available information, borders between disciplines get blurred and where successful research and its applications does not only require a firm basement in one discipline, but also enough “universal education”, as to be able to communicate with “experts” from other disciplines, and to find out and further explore the interfaces between different disciplines. Such a dialogue has been particularly far developed by the scientists working with “materials”, coming originally from mechanics, physics, and chemistry, and the engineering fields: civil, mechanical, biomedical. Traditionally, mechanicians and engineering scientists worked at the length scales “visible by the naked eye”, chemists a little lower, while physicists got more and more involved with the nature of matter as such, down to a scale where matter “becomes” energy. Since at least decade, however, the engineering scientists discovered the beauty and the truly worthwhile challenge to apply and extend their (mainly continuum) methods down to the “microscale”, as to shake hands with the computational chemists who work hard on delivering molecular models large enough to be representative for a “continuum material volume element”. Depending on the application, this shake-hands, still a somewhat open challenge, may be expected at a scale ranging from several nanometers to that of several micrometers. The present issue deals with this macro-micro exploration – leaving the other big challenge, the quantum-to-molecular physics transition with the chemists striving down towards the quantum level left aside here.

All eight contributions in this issue reflect the activities of engineering scientists venturing from traditional macroscopic scale down to microscopic scales. The main practical reason for that is that at the macroscopic scale, properties of biological material tend to show an extreme variability at the macroscopic scale, in contrast to traditional engineering materials where constant homogeneous macroscopic properties can be often gained directly from macroscopic tests. Thus, the art lies in finding the appropriate scale where again invariable material properties, namely properties of material constituents emerge; and in one way or the other, all contributions in this topical issue relate to this "quest for the appropriate smallest scale", and to how to bridge this scale to the larger one of the investigated scientific question or engineering application: Clearly, the appropriate scale depends on the overall question or engineering problem tackled – with several intereting problems and answers provided in this topical issue. In this context, we should always be reminded that multiscale mechanics is strongly driven by experimental research, actually providing information about the morphological features seen at different observation scales, and their mechanical properties. Thereby, a desirable situation would be characterized by having a fairly complete "picture" provided by a collection of state-of-the-art experimental techniques, applied to one and the same set of material samples. With this vision, (Hobatho et al) perform a "multiscale characterization of cortical bone", starting with a centimeter-sized whole-organ cartography of acoustically determined elastic properties at 100 microns resolution, via nanoindentation-derived elastic properties at the several microns scale, down to atomic force microscopic (AFM) images resolving collagen fibrils and mineral crystals in the several tens to hundreds of nanometers scale. These mechanics-based techniques are complemented by microscopic and spectroscopic studies on the same bones, spanning again millimeter-to-nanometer scales.

The following two contributions are based on the field of multiscale continuum micromechanics, which has proved as a particularly appropriate theoretical and computational approach to represent the mechanical interactions of the tissue-independent elementary building blocks in bone (molecular collagen and hydroxyapatite crystals at the scale of several to several tens of nanometers, both embedded into water filling the nanoporous spaces around them). Namely this technique allows one to translate these building blocks' tissue-depedent chemical concentrations, as well as all the porosities found between the nanoand the vascular scale, to bone tissue properties at again different scales, ranging from that of long collagen fibrils with hundreds of nanometers diameter, via extracellular bone matrix with several microns characteristic size, to cortical or trabecular bone material at the hundreds-of-microns to even millimeter scale. In order to integrate such approaches to the daily clinical practice, the quest for their relation to computer tomographic images has attracted the multiscale biomechanicians: This allows one to study the "effects of the axial variations of porosity and mineralization on the elastic properties of the human femoral neck", as described in the contribution of (Sansalone et al.), but the combination of X-ray physics at the basis of Computer Tomography, with intravoxel multiscale can also be extended to bone tissue engineering scaffolds deemed to trigger the healing of large bone defects, as described by (Luczynski et al), showing that "MicroCT/micromechanics-based Finite Element models and quasi-static unloading tests deliver consistent values for Young's modulus of rapid-prototyped polymer-ceramic tissue engineering scaffolds". These authors also describe nanoindentation on such scaffolds, as do (Khanna et al) on biological cell-seeded scaffolds, reporting on "AFM and nanoindentation studies of bone nodules on Chitosan-Polygalacturonic Acid-Hydroxyapatite Nanocomposites". Appropriate evaluation of nanoindentation can become itself a demanding theoretical and computional task, as shown by (Taffetani et al), in a study devoted to the "Modeling of the frequency response to dynamic nanoindentation of soft hydrated anisotropic materials: application to articular cartilage". However, the engineering science of biological materials is neither restricted to the osteochondral field, nor to continuum approaches: As one examples, the "elasto-damage modeling of biopolymer molecules response" by (Maceri et al) rests on coarse grain concepts bridging mechanical damage with enthalpy and entropy consideration, and it is easy to foresee the potential application of this model into a hierarchical approach to the multi-scale mechanics of tissues. On the other hand, the model of the spatially dependent mechanical properties of the axon during its growth", by (Garcia et al), quantifies mechanics-mediated neuronal growth. And clearly, mathematical modeling of biological materials is not necessarily restricted to solid mechanics, as (Mattei et al) employ computational fluid dynamics as to model the sedimentation processes in "functionally graded materials (FGMs) with predictable and controlled gradient profiles: computational modeling and realization".

We are positive that this collection of papers impressively shows the versatility and by no means exhausted capability of continuum (and discrete) mechanics for the deeper understanding of the intricate behavior of biological materials - and that it will inspire novel exploration attempts into the infinite amount of unsolved, but highly relevant problems in biological materials across different length scales.

Christian Hellmich
Vienna University of Technology
Institute for Mechanics of Materials and Structures
Vienna, Austria

Pasquale Vena
Poiltecnico di Milano
Department of Structural Engineering and IRCCS, IRCCS
Istituto Ortopedico Galeazzi
Milan, Italy