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Editorial

Inverse problems and material identification in tissue biomechanics

1. Introduction

This special issue follows the Euromech534 colloquium which was organized in Saint-Etienne, France from 29 to 31 May 2012 on the topic “Advanced Experimental Approaches and Inverse Problems in Tissue Biomechanics”. The objective of the colloquium was to foster the interaction and networking of those working in the general area of mechanics applied to biological tissues, materials and applications, throughout universities, industries, and government laboratories. The colloquium gathered 80 delegates from 20 different countries and served to facilitate a state of the art review of the recent advances in testing approaches, imaging techniques and inverse problems for applications in tissue mechanics and biomechanics.

There are many fields in medicine where accurate measurements of local tissue properties are needed. In general it is difficult to measure the mechanical properties of these materials directly and some kind of inverse approach is needed, where an experiment has to be simulated and the material parameters are adjusted until the model matches the experiment.

Several open questions are raised by inverse approaches in tissue biomechanics:

– Experimental measurements on biological tissues present many practical and theoretical difficulties. Experimental and numerical errors also increase the uncertainty, as do inadequate constitutive models.
– An inverse problem requires a computational model that can be solved repeatedly with different material parameters. This requires a model that can be solved quickly and reliably; these are not attributes one usually associates with computational models of biological tissues.
– Biological tissue mechanical behaviour exhibits special characteristics that may affect the mechanical response and disturb material identification, such as visco-elasticity, multi-scale properties, variability of properties and remodelling.
– Once the necessary experimental data and computational models are in place, it is essential to implement an appropriate optimization strategy to adjust the material parameters to give the best match with the experimental results, and to consider issues of uniqueness of the identified parameters. Where only a single parameter is optimized, for example the stiffness of the material, it is relatively easy to ensure that a global optimum has been found, but for complex models with many parameters there are often many different parameter sets that will produce equally good results.
– the question of uniqueness can be tackled by increasing the quantity of experimental data. To this purpose, tracking the full-field deformation of tissues using optical measurements or medical imaging techniques becomes quite commonplace but these novel measurement approaches have only been recently applied to material identification of biological tissues and they still have to be well calibrated and validated for them.

It has also been identified that in certain situations useful patient-specific results can be obtained without precise knowledge of patient-specific properties of tissues. This situation arises when computational biomechanical models can be loaded kinematically or when structures under consideration are approximately statically determinate. Problems that meet these requirements frequently arise in image-guided surgery (e.g. neurosurgery) and modelling and analysis of thin-walled biological organs.

2. Content of the special issue

The papers presented in this Special Issue address many of the above issues.

Several submissions address the problem of tracking the natural deformation of arteries in vivo using medical imaging and to identify material parameters from these data. For instance, Franquet et al. present a paper entitled “Identification of the in vivo elastic properties of common carotid arteries from MRI: a study on subjects with and without atherosclerosis”. This paper discusses the identifiability of the passive mechanical properties of the human common carotid artery from common Magnetic Resonance Imaging scans, taking into account the properties of the perivascular tissues. Another similar study is presented by Wittek et al. It is entitled “In Vivo Determination of Elastic Properties of the Human Aorta Based on 4D Ultrasound Data”. The aim is to derive the distribution of elastic properties across human aortas from common ultrasound data.

A few papers are focused on the potential of optical methods such as digital image correlation (DIC) for deriving the local deformation of the tissues in response to a loading experiment, and then to derive material parameters from them. For instance, Boyer et al. present a paper entitled "Assessment of the in-plane biomechanical properties of human skin using a Finite Element Model Updating approach combined with an optical full-field measurement on a new tensile device" where DIC is applied in vivo for the measurement of skin deformation. Bel-Brunon et al. used DIC for deriving the elastic and damage properties of liver capsules in their paper entitled "Compared prediction of the experimental failure of a thin fibrous tissue by two macroscopic damage models". The very specific question of fracture of fibrous tissues was addressed; this question will certainly generate many other inverse problems in the future as the topic of tissue fracture is one of the big challenges in biomechanics.

In a very interesting paper entitled "On a staggered iFEM approach to account for friction in compression testing of soft materials", Boel et al. also propose an approach based on DIC measurements to account for friction in classical compression tests carried out on soft tissues. Very sophisticated optical measurements have also been specifically developed by Genovese et al. for revisiting the characterization of vascular tissues. In their paper entitled "An Improved Panoramic Digital Image Correlation Method for Vascular Strain Analysis and Material Characterization", they show whole strain maps measured on mouse carotid arteries in response to internal pressurization. Thanks to these strain maps, the authors are able to highlight the mechanical heterogeneity of vessel walls and the role of collagen and elastin on the mechanical response.

A few papers present specific tests aimed at characterizing a very specific tissue or piece of tissue for which it is necessary to model faithfully the geometry and the boundary conditions of the biomechanical experiments in a finite element model (FEM) for setting up the inverse problem. Special features of biological tissues make this approach sometimes complex.

This is the case for instance when the piece of tissue is very heterogeneous as it is the case for the atherosclerotic plaques presented by Heiland et al. in their paper entitled "Identification of carotid plaque tissue properties using an experimental–numerical approach".

The question of variability of biomechanical properties can be another source of difficulty. For instance, Badir et al. characterize the mechanical properties of the uterine cervix and show extensive results in their paper "A novel procedure for the mechanical characterization of the uterine cervix during pregnancy".

Abyaneh et al. look at the mechanical properties of the cornea using nanoindentation and present a novel hybrid approach for this application in their paper entitled "A hybrid approach to determining cornea mechanical properties in vivo using a combination of nano-indentation and inverse finite element analysis".

An important challenge in biomechanics is also to characterize the mechanical behaviour of tissues at different strain rates and under dynamic loading. Inverse problems posed by impact loading of skeletal muscles are solved by Takaza et al. in their paper entitled "Passive Skeletal Muscle Response to Impact Loading: Experimental testing and inverse modelling".

Soft tissues generate many inverse problems but it was important to investigate the state of the art in bone biomechanics as well. An interesting review is presented by Zadpoor on inverse problems posed by bone biomechanics and mechanobiology in his paper entitled: "Open forward and inverse problems in theoretical modelling of bone tissue adaptation".

Eventually, inverse problems and material identification may arise in many situations of tissue biomechanics, but there are also many situations where inverse problems can be simplified or situations that do not require material identification for setting-up precise patient-specific models of the tissue response. About these situations, Miller and Lu present a very original paper entitled "On the prospect of patient-specific biomechanics without patient-specific properties of tissues" where two situations are reviewed where the deformations, strains and stresses in soft tissues can be derived without precise knowledge of the mechanical properties of materials.

3. Short-term challenges and future trends in inverse problems for material identification

3.1. *Mechanobiology*

Nowadays, it has become a common practice to combine video based full-field displacement measurements experienced by tissue samples in vitro, with custom inverse methods to infer (using nonlinear regression) the best-fit material parameters and the rupture stresses and strains. Similar approaches also exists for characterizing the material parameters of soft tissues in vivo, where advanced medical imaging can provide precise measurements of tissue deformation under different modes of action, and inverse methodologies are used to derive material properties from those data.

These approaches offer important possibilities for fundamental mechanobiology research which aims at gaining better insight in the growth, remodelling and ageing effects in biological tissues. It is well-known that biological soft tissues appear to develop, grow, remodel, and adapt so as to maintain particular mechanical metrics (e.g., stress) near target values. To accomplish this, tissues often develop regionally varying stiffness, strength and anisotropy.

Important challenges in material identification of biological tissues are now to develop and implement hybrid experimental–computational method to quantify these regional variations in properties in situ.

One of the biggest questions will still remain the uniqueness of solutions and it is advised to systematically validate inverse approaches with simulated data before implementing it on real experimental data.

3.2. Patient-specific computational biomechanics for medicine

We are witnessing an advent of patient-specific biomechanics that will bring in the future personalized treatments to sufferers all over the world. It is the current task of biomechanists to devise methods for clinically-relevant patient-specific modelling. One of the obstacles standing before the biomechanics community is the difficulty in obtaining patient-specific properties of tissues to be used in biomechanical models or reformulating computational mechanics problems in such a way that the results are weakly sensitive to the variation in mechanical properties of simulated continua.

3.3. Efficient solution methods for computational biomechanics models

Optimization schemes often employed in inverse problem approaches usually require multiple solutions to a sophisticated finite element model of an organ. Very efficient solution methods are therefore necessary for this approach to be feasible. One possibility is to harness the power of Graphics Processors that offer very high performance at low cost. There is also a need for more reliable solution algorithms that need less user input to ensure convergence.

4. Conclusion

Finally, inverse problems and material identification are an exciting and fast growing area of research in tissue biomechanics at the moment. New approaches are needed to address the short-term challenges and we hope that the papers presented in this special issue may make a useful contribution to this purpose.

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