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Research Paper

On the prospect of patient-specific biomechanics without patient-specific properties of tissues

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A B S T R A C T

This paper presents main theses of two keynote lectures delivered at Euromech Colloquium “Advanced experimental approaches and inverse problems in tissue biomechanics” held in Saint Etienne in June 2012. 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 modeling. 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. We postulate that focusing on reformulating computational mechanics problems in such a way that the results are weakly sensitive to the variation in mechanical properties of simulated continua is more likely to bear fruit in near future. We consider two types of problems: (i) displacement-zero traction problems whose solutions in displacements are weakly sensitive to mechanical properties of the considered continuum; and (ii) problems that are approximately statically determinate and therefore their solutions in stresses are also weakly sensitive to mechanical properties of constituents. We demonstrate that the kinematically loaded biomechanical models of the first type are applicable in the field of image-guided surgery where the current, intraoperative configuration of a soft organ is of critical importance. We show that sac-like membranes, which are prototypes of many thin-walled biological organs, are approximately statically determinate and therefore useful solutions for wall stress can be obtained without the knowledge of the wall's properties. We demonstrate the clinical applicability and effectiveness of the proposed methods using examples from modeling neurosurgery and intracranial aneurysms.

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1. Introduction

Computational mechanics has enabled technological developments in almost every area of our lives. One of the greatest challenges for mechanists is to extend the success of computational mechanics to fields outside traditional engineering, in particular to biology, biomedical sciences, and medicine (Oden et al., 2003). By extending the surgeon's ability to plan and carry out surgical interventions more accurately and with less trauma, computer-integrated surgery (CIS) systems will

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improve clinical outcomes and the efficiency of health care delivery. CIS systems will have a similar impact on surgery to that long since realized in computer-aided design (CAD) and computer-integrated manufacturing (CIM).

Before this grand vision can be realized, a number of theoretical and technological difficulties associated with accurate and clinically practical simulation of the mechanical responses of human organs must be addressed. One of the most challenging is the problem of identifying patient-specific properties of tissues. The difficulty of obtaining patient-specific mechanical properties of soft tissues has stimulated a lot of research in experimental mechanics, leading in particular to the application of MR and ultrasound elastography initially developed for diagnosis (Muthupillai et al., 1995; Sarvazyan et al., 1998; Xu et al., 2007), as well as renewed interest in inverse problems (Gee et al., 2010; Lu and Zhao, 2009; Sinkus et al., 2010; Zhao et al., 2009).

In this paper, summarizing the content of two keynotes delivered at Euromech Colloquium "Advanced experimental approaches and inverse problems in tissue biomechanics" held in Saint Etienne in June 2012, we postulate that focusing on reformulating computational mechanics problems in such a way that the results are weakly sensitive to the variation in mechanical properties of simulated continua is more likely to bear fruit in near future. In particular we focus on two types of problems:

(i) pure-displacement (Ciarlet, 1988) and displacement-zero traction problems (Miller and Wittek, 2006; Miller et al., 2010) whose solutions in displacements are weakly sensitive to mechanical properties of the considered continuum; and
(ii) problems that are approximately statically determinate and therefore their solutions in stresses are weakly sensitive to mechanical properties of constituents (Gere and Timoshenko, 1997; Lu et al., 2008; Timoshenko, 1981).

In the field of patient-specific biomechanics the first type of problems is prevalent in the area of image-guided surgery, where we are interested in the current, intraoperative configuration of an organ of interest and have at our disposal detailed preoperative images as well as some, often very limited, intraoperative information. Therefore it is possible to determine deformations of soft organs during surgery without knowledge of patient specific properties of tissues. The second type of problems has been identified in the field of biomechanics of intracranial aneurysms that can be approximately modeled as thin-walled structures that are known to be statically determinate. If we formulate the equilibrium boundary value problem inversely, as explained in Section 2.2, we are able to determine the aneurysm wall stress distribution without the knowledge of patient-specific mechanical properties of the tissues comprising the wall.

This article is organized as follows. In Section 2 we put forward the arguments why in certain cases we are able to obtain meaningful patient-specific results without the knowledge of particular patient's tissue properties. In Section 3 we give application examples taken from the areas of neurosurgical simulation and aneurysm modeling. Section 4 contains discussion and conclusions.

2. Theoretical arguments for unimportance of mechanical properties of tissues

2.1. *Pure displacement and displacement-zero traction problems*

As suggested in papers (Miller, 2005a; Miller and Wittek, 2006), in problems where loading is prescribed as forced motion of boundaries, the unknown deformation field within the domain depends very weakly on the mechanical properties of the continuum. To see why, first consider an (oversimplified) quasistatic, linear elastic case. Then the following dimensional reasoning applies: the loading is provided by the enforced motion of boundaries measured in meters [m]; the result of computations are displacements measured in [m]; therefore the result cannot depend on the stress parameter measured in [$\mathrm{Pa}=N/m^2$]. We should note here that the result can depend on (dimensionless) Poisson's ratio and on (dimensionless) ratios of stress parameters if the model contains materials with different stiffness. The dependence on the volumetric response (e.g., Poisson's ratio) is of minor consequence for soft organ biomechanics because tissues such as the brain, liver, kidney or prostate are considered almost incompressible (Bilston, 2011; McAnearney et al., 2010; Miller, 2000, 2011).

In the general nonlinear case the displacement results will still remain insensitive to the stress parameter appearing in the nonlinear material law, but may depend on the particular form of that law (as the functional form of a constitutive law does not have a dimension). This dependency can, however, be expected to be rather weak, as explicitly demonstrated in Miller (2001, 2005b) where the shapes of compressed and extended cylinders were shown to be essentially independent of the material law used for the cylinder's material, see Fig. 1. These results suggest a move away from mechanics towards kinematics: the main quantities of interest in this approach are displacements, strains and their histories. Insensitivity to material properties is the feature of great importance in biomechanical modeling, where there are always uncertainties in patient-specific properties of tissues.

2.2. *Statically determinate structures*

As discussed in virtually any elementary solid mechanics text, the stress in a deformable solid depends on the applied load, geometry, boundary conditions and properties of the material comprising the body. There is, however, a family of structures in which the stress field depends on the load, the boundary conditions and the geometry, but not the material property. Structures as such are called statically determinate (Gere and Timoshenko, 1997; Timoshenko, 1981). Truly statically determinate systems are rare in finite deformation regime, but there are problems that are approximately so in the sense that the stress distribution depends weakly on the material properties. Exploiting this feature, we may obtain reasonably accurate stress solutions without invoking accurate material description, which we know is difficult to obtain in biological systems.

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