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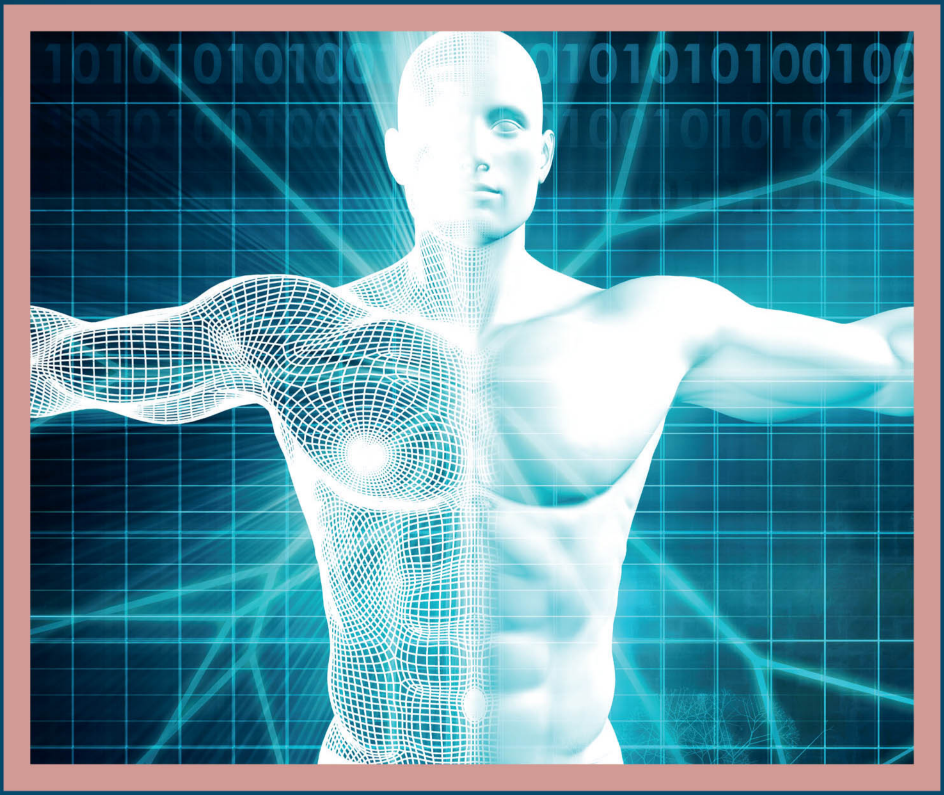

BIOMECHANICS OF LIVING ORGANS

HYPERELASTIC CONSTITUTIVE LAWS FOR FINITE ELEMENT MODELING

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Introduction

Biomechanics of human soft tissues has been an emerging research field since the publication, in 1981, of the book "*Biomechanics: Mechanical Properties of Living Tissues*" by Yuan-Cheng Fung[1]. Since that date, many groups in the world have proposed biomechanical models of soft organs to study their physiology and mechanical behavior. Such organs indeed deform under physiological conditions (such as muscle activations or interactions with other tissues) or because of the mechanical interaction with the surgical gesture. For example, modeling human heart deformations requires an accurate description of the passive and active behaviors of cardiac fibers and their coupling with the blood flow. Assisting a surgical gesture to compensate brain shift during tumor resection needs to model brain's deformations and its mechanical interactions with the skull surface and with the surgical tools.

Human soft tissues are complex materials that can exhibit non-linear, time dependent, inhomogeneous and anisotropic behaviors. Modeling such behaviors is usually proposed with the partial differential equations (PDE) of Continuum Mechanics that are numerically solved through the Finite Element (FE) Method. Elaborating a subject-specific FE model is a long and tedious task that requires (1) to collect data as concerns the geometry of the organ, (2) to propose a constitutive model and to estimate its parameters for the organ soft tissues, (3) to define boundary conditions describing the mechanical interactions with the organ, and (4) to solve the PDE with the FE method, using a 3D meshing of the organ's geometry and a numerical simulation. While estimating the subject-specific 3D geometry of the organ (mainly using segmentation techniques applied to 3D images such as CT or MRI) and solving the PDE (using dedicated FE software) are now quite straightforward tasks, the choice for a constitutive model of the organ is still an open question source of many works. Indeed, for each organ of the human body, various constitutive models have been proposed raising questions such as "*Should we consider the tissue deformations as large enough to need a hyperelastic framework?*" ; "*If yes, which strain energy functions are the most appropriate to model the passive and active states of the living tissue?*" ; *"How can we model muscle contraction, damaged biological tissues, soft tissue growth and remodeling?"*; "*Should we take into account viscosity?*" ; "*Do the proposed energy functions have a physical meaning?*".

Biomechanics of Living Organs: Hyperelastic Constitutive Laws for Finite Element Modeling is the first book to cover finite element biomechanical modeling of each organ in the human body. This book aims at (1) introducing the basic notions as concerns the hyperelastic constitutive laws for biological living tissues and (2) describing the main human organs, from the head to the foot, and proposing for each organ the most adapted constitutive model. For

[1] Fung Y.C., 1981. *Biomechanics: Mechanical Properties of Living Tissues*. Springer, New York.

this, we have gathered the key opinion scientists who propose review chapters focused on the constitutive laws that should be considered as a reference for each organ. The first part of the book is a basic description of the equations that govern hyperelasticity, with focuses on isotropic vs anisotropic passive or active tissues, visco-hyperelastic constitutive models, formulations for soft tissue growth and remodeling, as well as damaged tissues. Then, part II provides review chapters for the reference constitutive models of "*passive*" soft organs, from the brain to the uterus. For all these organs, tissues deformations are due to external loading such as gravity and mechanical interactions with surrounding tissues or with the surgical tools. Part III concerns "*active*" organs which shapes are also determined by the recruitment of muscles, some of them being internal to the structure, in such a way that, as for the elephant trunk, part of the organ is responsible for its own deformation. This is the case for the face, the tongue, the upper airways and the heart. Finally, part IV or the book describes the constitutive models that should be provided when modeling musculo-skeletal structures such as the spine, the thigh, the calf and the foot.

It is important to note that the key opinion scientists who have reviewed in this book the most efficient constitutive models of the human organs have all provided full FE implementations of organs models. They should, to our point of view, be considered as references for students, researchers, clinicians and industrial partners who want to build and use organ biomechanical models in the future. It is our hope this book will provide the reader a comprehensive overview of the state-of-the-art in hyperelastic constitutive laws for organs' FE modeling. We would like to thank all the authors and reviewers for their contributions and their enthusiasm during the writing of this book.

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Abstract

Biomechanics of human soft tissues has been an emerging research field since the publication, in 1981, of the book "*Biomechanics: Mechanical Properties of Living Tissues*" by Yuan-Cheng Fung. Since that date, many groups in the world have proposed biomechanical models of soft organs to study their physiology and mechanical behavior. *Biomechanics of Living Organs: Hyperelastic Constitutive Laws for Finite Element Modeling* is the first book to cover finite element biomechanical modeling of each organ in the human body. This book aims at (1) introducing the basic notions as concerns the hyperelastic constitutive laws for biological living tissues and (2) describing the main human organs, from the head to the foot, and proposing for each organ the most adapted constitutive model. For this, we have gathered the key opinion scientists who propose review chapters focused on the constitutive laws that should be considered as a reference for each organ. It is our hope this book will provide the reader a comprehensive overview of the state-of-the-art in hyperelastic constitutive laws for organs' Finite Element modeling, along with a deeper understanding of the associated problems that will face students, researchers, clinicians and industrial partners in the future.

The authors

Yohan Payan and Jacques Ohayon are PhD senior researchers belonging to TIMC-IMAG Laboratory (CNRS & Univ. Grenoble Alpes, France). They are both members of the International French Society of Biomechanics from which they received the Senior Prize, respectively in 2012 and 2016. With an engineering background and a CNRS senior position, Yohan Payan main research interests concern the biomechanical modelling of soft tissues, with applications to Computer Assisted Medical Interventions (CAMI). He is the deputy director of TIMC-IMAG laboratory and leads the CAMI team. Jacques Ohayon is professor of Applied Mechanics at the Engineering School Polytech Annecy-Chambéry – University Savoie Mont-Blanc and is part of the TIMC-IMAG DyCTiM team (Cellular/Tissular Dynamics and Functional Microscopy). His research interests are in biomechanics of atherosclerotic plaque, plaque detection, plaque rupture prediction, plaque growth and development of new clinical tools for imaging the elasticity of vulnerable plaque based on clinical OCT, MRI and IVUS sequences.

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