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Review

The mechanical behavior of skin: Structures and models for the finite element analysis

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Soft biological tissues are complex materials with a large structural variety, with differences in behavior, but with some common characteristics. Skin is an archetypal soft tissue which presents many common characteristics to other soft biological tissues, like being a multilayer collagen-reinforced structure, with nonlinear behavior, anisotropy, viscosity, preconditioning effects, internal stresses and tissue growth and adaptation. Departing from a detailed description of the structures of the skin and the experimental evidence, we herein analyze the different modeling approaches in the literature for the distinct aspects of the skin behavior, with attention to the implementation in finite element codes.

Contents

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1. Introduction

The scientific interest for describing biological tissues under a mechanical, mathematical and physical conception is not recent. It is well-known that the first extensive work was performed probably by Leonardo da Vinci at the beginning of the 16th century giving a detailed graphic description of the anatomy of the human body [1]. In 1667, Borelli, described the movements of the animals from a physical and mathematical viewpoint, paying special attention to the role played by muscles [2]. The Langer lines describing the human skin anisotropy and its tension, dates from 1861 [3] and are well-known to any skin surgeon. In 1867, Wolff interpreted the architecture of trabeculae and cavities of bones as a structural adaptation to different mechanical loading, binding this adaptation to bone growth [4]. Roy [5] studied the elastic properties of arterial walls experimentally in 1880, and in 1917, Thompson [6] studied why certain organisms grew up to have a certain shape. As Wolff, Thompson described the coincidence between the arrangement of the femur trabeculae and the stress lines of this bone conceived as a loaded structure. Probably, biomechanics started with these works, although it was not until the mid-20th century, coinciding with the development of nonlinear continuum mechanics, that biomechanics arises as a distinct discipline [7,8].

1.1. The role of computational mechanics in biomechanics

The last half of the 20th century was the explosion of continuum mechanics and of numerical methods in engineering, specially of the finite elements [9]. Continuum and computational mechanics are now playing an important role in the biomechanics field, returning them a new momentum [10]. Biological systems constitute new *structures* to be studied and characterized which require new continuum and micro-mechanical models as well as new computational procedures [11]. Biological tissues are complex microstructures with highly nonlinear behavior; skin sustains deformations of the order of 50% [12] with changes of stiffness of orders of magnitude [13,12]. The generally large nonhomogeneous deformations present, and the complex geometries, require efficient numerical methods as the finite element method [9]. In contrast to what is done for classical, geometrically-determined, engineering products, where the effort was placed into importing finite element meshes from CAD programs, finite element meshing of organs is to be obtained mainly from medical images [14–16] because the analysis of the mechanical behavior of organs should include the actual, patient-related, geometric and material data [17].

Biomechanics studies a large variety of biological processes and the mechanical behavior of many distinct type of biological materials. In this review we focus mainly in models that may be suitable for the mechanical analysis of skin by finite elements, although much work in this area is common also to analytical procedures in mainly homogeneous deformations and to other biological tissues (heart wall, fascia, tendons, ligaments, articular cartilage, blood vessels, etc.). Some of these tissues, as skin, are called connective tissues because their main role is to connect and to protect the human body as well as its other components, [18–20].

1.2. Purpose of this review

Although much has been done in the relatively new field of the mechanics of biological tissues and their computational simulation, in contrast to the classical computational mechanics of solids, there is not a well accepted and defined approach, successful in the finite element simulation of processes in such materials, as for example in the simulation of surgery in organs and, specially in skin. Accurate predictions are desired for these procedures in order, for example, to develop efficient and accurate numerical simulators for plastic surgery in skin [21], or for pressure ulcers prevention through the simulation of the loading of skin [22], among many others. However, there is not even a widely accepted approach in modeling just the elastic behavior of such tissues. Therefore, the purpose of this contribution is, departing from the important understanding of the mechanical behavior of skin, from its microstructure and from the available experimental evidence, to review the main modeling approaches for soft fibrous biological materials to model non-homogeneous deformation states in skin through finite element analysis. We hope that this review may serve as a good starting point for researchers involved in modeling skin through finite element analysis.

The paper is organized as follows. We first analyze the structures of the skin and of the main contributors to the mechanical behavior: collagen and elastin. Then we analyze the experimental evidence which determines the behavior and fundamental hypotheses. After reviewing the stress and strain measures typically employed, we address the usual models to represent the hyperelastic (conservative) contribution, which is the basis for any formulation including other aspects. Since soft biological tissues present relevant inelastic effects due to an important time-dependent component and to preconditioning effects [11,7], we also address viscoelastic and damage models.

Given the vast literature in the topic, in order to obtain a desirable condense yet analytical presentation, many valuable works will be omitted; only some representative ones for each approach will be addressed.