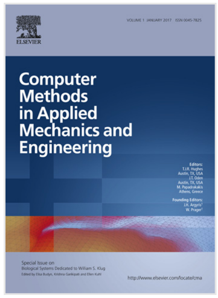
Accepted Manuscript



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PII: S0045-7825(16)30419-4
DOI: http://dx.doi.org/10.1016/j.cma.2017.02.028
Reference: CMA 11355

To appear in: *Comput. Methods Appl. Mech. Engrg.*

Received date: 23 May 2016
Revised date: 15 February 2017
Accepted date: 20 February 2017

Please cite this article as: G.D. Ares, P.J. Blanco, S.A. Urquiza, R.A. Feijóo, Identification of residual stresses in multi-layered arterial wall tissues using a variational framework, *Comput. Methods Appl. Mech. Engrg.* (2017), http://dx.doi.org/10.1016/j.cma.2017.02.028

Identification of residual stresses in multi-layered arterial wall tissues using a variational framework

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Abstract

In the past decades a considerable amount of literature has been published addressing the study of the mechanical behavior of arterial walls. Ex-vivo experimentation made possible the development of constitutive models and the characterization of material parameters contributing to the understanding of the mechanobiological response of vascular tissues. Moreover, the existence of residual stresses in configurations free of load was revealed, and its impact in the general stress state of the tissue was quantified. In recent years, data assimilation techniques have seen a rapid development in cardiovascular modeling field, primarily focusing on the estimation of material parameters for arterial wall segments using information provided by medical imaging as well as by in-vitro settings. However, concerning the estimation of residual stresses, this research field is in its early stages, and much work is still required for the full functional characterization of arterial tissues.

In this context, a conceptual variational framework for the development of residual stress estimation tools is proposed. Particularly, a variational formulation for the characterization of residual deformations and the associated stresses in arterial walls, based on full displacement field measurements of the vessel, is presented. Considering as known data the material parameters characterizing the behavior of the tissue and a set of arterial wall configurations at equilibrium with well defined pressure loads, we propose a cost functional that measures the mechanical imbalance caused by the lack of knowledge of residual stresses. In this manner, the characterization of residual stresses becomes a problem of minimizing such cost functional. Three numerical examples are presented highlighting the potential of the proposed approach. Among these examples, the characterization of residual stresses in a cylindrical geometry representing a three-layered aorta artery is performed.

Keywords: Residual deformations, residual stresses, arterial wall, characterization, variational formulation

1. Introduction

As it is well known, in order to realistically model and simulate the behavior of arterial tissues it is necessary to account for the different mechanical properties of arterial wall layers (intima, media, adventitia) considering the interaction of the structurally relevant components, namely: elastin, collagen fibers and smooth muscle cells [1]. A considerable amount of literature has been published addressing the study of the constitutive behavior of these soft tissues, developing comprehensive models [2, 3], and performing parameter estimation based on ex-vivo experimental data [4, 5]. However, it has also been recognized [2, 6, 7] that the in-vivo unloaded configuration of any vascular district is neither stress-free nor strain-free [8]. This led to an increasing number of investigations [9, 10] studying the effects of residual stresses (RSs) in arterial wall mechanics. In the last decades a shifting in the role researchers assign to RSs has taken place, from conceiving RSs as a mere side effect of growth to a conception in which RSs are viewed as an adaptive and protective mechanism. Certainly, residual strains and stresses have a functional role in determining suitable mechanobiological conditions in vascular vessels [11, 12]. In fact, arteries are living tissues that continuously adapt to their environment and to external stimuli [13, 14, 15]. This adaptation is mediated by growth and remodeling processes that lead to the occurrence of self-equilibrated RSs. In this connection, it has been pointed out [16] that RSs contribute to the transmural uniformity of the circumferential strains under physiological conditions, lowering stress gradients across the thickness of the vessel within each layer [17].

Reported experimental observations show that when an arterial segment is removed from its surroundings, RSs are manifested through the retraction of the vessel in the longitudinal direction as well as through the appearance of an opening angle when the wall is radially cut all along its axis. Moreover, in relatively recent works [5, 7], it has been observed that different levels of RSs are associated to the different constituent layers of the arterial wall. Most ef-