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A method for incorporating three-dimensional residual stretches/stresses into patient-specific finite element simulations of arteries

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ABSTRACT

The existence of residual stresses in human arteries has long been shown experimentally. Researchers have also demonstrated that residual stresses have a significant effect on the distribution of physiological stresses within arterial tissues, and hence on their development, *e.g.*, stress-modulated remodeling. Through progress in medical imaging, image analysis and finite element (FE) meshing tools it is now possible to construct *in vivo* patient-specific geometries and thus to study specific, clinically relevant problems in arterial mechanics via FE simulations. Classical continuum mechanics and FE methods assume that constitutive models and the corresponding simulations start from unloaded, stress-free reference configurations while the boundary-value problem of interest represents a loaded geometry and includes residual stresses. We present a pragmatic methodology to simultaneously account for both (i) the three-dimensional (3-D) residual stress distributions in the arterial tissue layers, and (ii) the equilibrium of the *in vivo* patient-specific geometry with the known boundary conditions. We base our methodology on analytically determined residual stress distributions (Holzapfel and Ogden, 2010, J. R. Soc. Interface 7, 787–799) and calibrate it using data on residual deformations (Holzapfel et al., 2007, Ann. Biomed. Eng. 35, 530–545). We demonstrate our methodology on three patient-specific FE simulations calibrated using experimental data. All data employed here are generated from human tissues – both the aorta and thrombus, and their respective layers – including the geometries determined from magnetic resonance images, and material properties and 3-D residual stretches determined from mechanical experiments. We study the effect of 3-D residual stresses on the distribution of physiological stresses in the aortic layers (intima, media, adventitia) and the layers of the intraluminal thrombus (luminal, medial, abluminal) by comparing three types of FE simulations: (i) conventional calculations; (ii) calculations accounting only for prestresses; (iii) calculations including both 3-D

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residual stresses and prestresses. Our results show that including residual stresses in patient-specific simulations of arterial tissues significantly impacts both the global (organ-level) deformations and the stress distributions within the arterial tissue (and its layers). Our method produces circumferential Cauchy stress distributions that are more uniform through the tissue thickness (*i.e.*, smaller stress gradients in the local radial directions) compared to both the conventional and prestressing calculations. Such methods, combined with appropriate experimental data, aim at increasing the accuracy of classical FE analyses for patient-specific studies in computational biomechanics and may lead to increased clinical application of simulation tools.

1. Introduction

Fung (1983) and Vaishnav and Vossoughi (1983) independently confirmed the existence of residual stresses in arteries. These residual stresses tend to homogenize the stress distribution within each arterial layer in the physiological state (Chuong and Fung, 1983, 1986; Fung, 1991). Numerous studies have shown that the inclusion of residual stresses in analyses of arteries under physiological loading conditions substantially reduces the variation in circumferential and axial stresses within the arterial wall (Vaishnav and Vossoughi, 1987; Matsumoto and Hayashi, 1996; Delfino et al., 1997; Holzapfel et al., 2000; Peterson and Okamoto, 2000; Humphrey, 2002; Raghavan et al., 2004). Since residual stresses significantly affect the total stress state in the tissue, they also have significant impact on the *in vivo* state and development of arterial tissues. Examples include stress-modulated remodeling of arteries in health and disease (*e.g.*, atherosclerosis and hypertension) (Takamizawa and Hayashi, 1987; Liu and Fung, 1989; Rodriguez et al., 1994; Taber, 1995; Taber and Eggers, 1996; Rachev, 1997).

Through progress in medical imaging, image analysis and finite element (FE) meshing tools it is now possible to extract patient-specific geometries from medical images of aortas and abdominal aortic aneurysms (AAAs), and thus to study specific, clinically relevant problems in arterial mechanics via FE simulations. Such simulations allow additional insight into both human physiology and pathophysiology. The final aim of such simulations is to provide improved analysis tools and patient-specific information to help clinicians diagnose and treat arterial pathologies. Medical imaging is performed *in vivo*, and hence the reconstructed model geometry in the problem of interest represents the *in vivo* state, *e.g.*, the aorta and AAA at physiological blood pressure. However, classical continuum mechanics and FE methods assume that constitutive models and the corresponding simulations start from an unloaded, stress-free reference configuration.

Two problems exist when applying such conventional approaches to patient-specific simulations of arteries: (i) the *in vivo* determined 'initial' geometry is not an unloaded reference configuration; (ii) the unloaded tissue itself is residually stressed. Computational methods of prestressing the FE model overcome the first problem so that, *e.g.*, the initial (image derived) geometry is in equilibrium with the known physiological loads, *cf.*, Gee et al. (2009) and Weisbecker et al. (2014). The second problem, that of *in vivo* residual stresses in patient-specific simulations, has still not been thoroughly addressed in the biomechanics literature, hence the motivation for our current study.

There have been many theoretical studies investigating the causes and effects of residual stresses in arteries, *cf.*, *e.g.*, Bustamante and Holzapfel (2010), Holzapfel and Ogden (2010), Ren (2013), Schröder and Brinkhues (2014) and, Waffenschmidt and Menzel (2014), but such works are outside our current focus on patient-specific FE-based simulations. Alastrué et al. (2007a) introduced a computational method to account for residual stresses in patient-specific simulations of arteries based on a single so-called 'opening angle' determined from a classical residual stress experiment (*cf.*, *e.g.*, Fung, 1983). They applied a composition of deformation gradients to account for homogeneous deformation of an arterial ring from an opened (assumed as stress free) to a closed (residually stressed but unloaded) configuration that differs (hopefully little!) from the *in vivo* patient-specific geometry due to non-compatibility issues. They exercised their method on a slice of a human coronary artery and a 3-D human iliac artery obtained by segmenting computed tomography images. Computational models, residually stressed by this method, reproduce the opening angle experiment with reasonable accuracy. Furthermore, patient-specific simulations under *in vivo* conditions, *i.e.*, applied internal pressure, demonstrate that the effect of residual stresses is significant, where transmural gradients change signs in the medial layer and stresses become nearly constant in the adventitia. In their analyses the authors did not account for the fact that the *in vivo* determined geometry is in equilibrium with physiological loads.

Later, Alastrué et al. (2010) proposed an extended numerical framework for patient-specific modeling of vascular tissue in order to obtain a residually stressed and geometrically consistent model of the patient. They accounted for residual stresses via their previously published approach (Alastrué et al., 2007a), while incorporating prestresses due to physiological loads by using an iterative approach based on a multiplicative decomposition of the deformation gradient. They demonstrated their framework by reconstructing a human carotid bifurcation from angiographic images, assuming a constant wall thickness for the artery and using a single set of material parameters experimentally determined from porcine tissue. Results show that incorporating residual