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A constitutive model for vascular tissue that integrates fibril, fiber and continuum levels with application to the isotropic and passive properties of the infrarenal aorta

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ABSTRACT

A fundamental understanding of the mechanical properties of the extracellular matrix (ECM) is critically important to quantify the amount of macroscopic stress and/or strain transmitted to the cellular level of vascular tissue. Structural constitutive models integrate histological and mechanical information, and hence, allocate stress and strain to the different microstructural components of the vascular wall. The present work proposes a novel multi-scale structural constitutive model of passive vascular tissue, where collagen fibers are assembled by proteoglycan (PG) cross-linked collagen fibrils and reinforce an otherwise isotropic matrix material. Multiplicative kinematics account for the straightening and stretching of collagen fibrils, and an orientation density function captures the spatial organization of collagen fibers in the tissue. Mechanical and structural assumptions at the collagen fibril level define a piece-wise analytical stress–stretch response of collagen fibers, which in turn is integrated over the unit sphere to constitute the tissue's macroscopic mechanical properties. The proposed model displays the salient macroscopic features of vascular tissue, and employs the material and structural parameters of clear physical meaning. Likewise, the constitutive concept renders a highly efficient multi-scale structural approach that allows for the numerical analysis at the organ level. Model parameters were estimated from isotropic mean-population data of the normal and aneurysmatic aortic wall and used to predict in-vivo stress states of patient-specific vascular geometries, thought to demonstrate the robustness of the particular Finite Element (FE) implementation. The collagen fibril level of the multi-scale constitutive formulation provided an interface to integrate vascular wall biology and to account for collagen turnover.

1. Introduction

The extracellular matrix (ECM) provides an essential supporting framework for the structural and functional properties of vessel walls. The ECM mainly contains elastin, collagen, and proteoglycans (PGs) (Carey, 1991) and their three-dimensional organization is vital to accomplish proper physiological functions. The ECM, therefore, rather than being merely a system of scaffolding for the surrounding cells, is an active mechanical structure that controls the micro-mechanical and macro-mechanical environments to which vascular tissue is exposed. Specifically, a proper understanding of the mechanical properties of the ECM is critically important to estimate and quantify the amount of stress and/or strain transmitted from the macroscopic to the cellular levels of vascular tissue.

Constitutive modeling of vascular tissue is an active field of research and numerous descriptions have been reported. However, the phenomenological approaches (Vaishnav et al., 1972; Fung et al., 1979; Chuong and Fung, 1983; Takamizawa and Hayashi, 1987; Humphrey, 1995; Delfino et al., 1997) that have been successfully used to fit experimental data cannot allocate stress or strain to the different histological constituents in the vascular wall. Structural constitutive descriptions (Lanir, 1983; Wuyts et al., 1995; Holzapfel et al., 2000; Holzapfel et al., 2002; Zulliger et al., 2004; Gasser et al., 2006; Gasser, 2011) overcome this limitation and integrate histological and mechanical information of the arterial wall.

Specifically, collagen fibers in the vascular wall have a major impact on the mechanical properties at higher loads (Roach and Burton, 1957; Greenwald and Berry, 1980), i.e. the condition experienced by the aneurysm wall. In addition to the volume fraction of collagen, its spatial arrangement, including the spread in orientations

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