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Micromechanical modeling of elastic properties of cortical bone accounting for anisotropy of dense tissue

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ABSTRACT

The paper analyzes the connection between microstructure of the osteonal cortical bone and its overall elastic properties. The existing models either neglect anisotropy of the dense tissue or simplify cortical bone microstructure (accounting for Haversian canals only). These simplifications (related mostly to insufficient mathematical apparatus) complicate quantitative analysis of the effect of microstructural changes – produced by age, microgravity, or some diseases – on the overall mechanical performance of cortical bone. The present analysis fills this gap; it accounts for anisotropy of the dense tissue and uses realistic model of the porous microstructure. The approach is based on recent results of Sevostianov et al. (2005) and Saadat et al. (2012) on inhomogeneities in a transversely-isotropic material. Bone's microstructure is modeled according to books of Martin and Burr (1989), Currey (2002), and Fung (1993) and includes four main families of pores. The calculated elastic constants for porous cortical bone are in agreement with available experimental data. The influence of each of the pore types on the overall moduli is examined.

1. Introduction

In this paper, we develop an analytical model of the effective anisotropic elastic properties of cortical bone in relation to the structure of its porous space. For this goal, we use the methodology of compliance contribution tensors first proposed by Horii and Nemat-Nasser (1983) and developed in works of Kachanov et al. (1994) and Sevostianov and Kachanov (2002). In contrast with previous modeling, we combine an account for anisotropy of dense tissue with a realistic model of microstructure that includes multiple systems of pores and canals typical for cortical bone.

Bone, as many other heterogeneous materials, is a complex arrangement, resulting in the microstructure of bone being hierarchical in nature. The microstructure at each of the levels produces a significant effect on its overall physical and mechanical properties. The structural and mechanical properties of the cortical bone, and a theoretical analysis of the connection between the structure of the porous space and the overall properties of the bone, has attracted the attention of many research groups for several decades. This interest has resulted in detailed descriptions of the structural features of bone at the macroscopic level, as well as the mechanical behavior of bone.

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Morphology of the cortical bone has been well studied and the overall elastic moduli have been measured in a number of experiments starting from 1960s. Lang (1969, 1970) assumed that the cortical bone is transversely isotropic (the plane normal to Haversian canals being the plane of isotropy) and measured the five elastic constants of dry bone. Reilly and Burstein (1975), Katz et al. (1984) and Van Buskirk and Ashman (1981) measured the anisotropic moduli ultrasonically and showed that in general, cortical bone possesses orthotropic elastic properties. However stiffnesses in multiple different directions normal to Haversian canals do not vary considerably, so much so that the deviation from transversal isotropy does not exceed 10%. Direct mechanical tests performed by Zioupos et al. (1995) also confirmed closeness to transversal isotropy, although the measured values of elastic stiffnesses were smaller than the ones measured ultrasonically, probably due to inelastic deformation.

Analytically, the most common model used to represent cortical bone is the "parallel fibers" approach. Generally, it consists of two phases, the first of which is to consider a single osteon as an elongated pore, representing a Haversian canal, surrounded by lamellae of dense mineralized tissue. The second level represents the lamellae as a fiber reinforced composite of collagen fibers in hydroxyapatite matrix. In the simplest form of the parallel fiber approach, Stech (1967) analyzed the overall anisotropy of cortical bone by considering parallel cylindrical pores surrounded by layered bone tissue without any pores within the lamellae. Later, a model emphasizing the hierarchical structure of cortical bone considered the impact on the effective elastic constants of both the porous space modeled as a set of parallel Haversian canals and the microstructure of the dense mineralized tissue, which was modeled as a fiber reinforced composite (Katz, 1981). Sevostianov and Kachanov (2000) applied the results of Eshelby's solutions for pores of different shapes to estimate the impact of the porous microstructure on the overall elastic constants of osteonal cortical bone in a micromechanical model approach. They considered a more appropriate system of pores that includes Haversian canals, osteocyte lacunae, Volkman's canals and canaliculi. The properties of the bone matrix, however were taken to be isotropic. Dong and Guo (2006) model cortical bone as a set of parallel circular Haversian canals embedded in a transversely-isotropic matrix. Later, Martínez-Reina et al. (2010) created a model that also considers cortical bone to be transversely isotropic, but expands the porosity to include canaliculi on the second level as well as takes into consideration the effects of water within the pores. The main advantage of this model that sets it apart is the ability to vary the mineral content of bone. Parnell et al. (2011) took the parallel fiber approach one step further by considering 3-phases; a polymer matrix, pores, and reinforcing particles. The Yoon and Cowin (2008a) model looks at the modulus of elasticity for a single osteonal lamellae. They view the hydroxyapatite and collagen in the bone matrix as embedded with water. This type of model agrees with many assumptions made about bone within the work presented in this paper, because the anisotropic behavior of the bone matrix is been taken into account and it demonstrates that the mechanical properties of cortical bone are highly dependent on its porosity. Nikolov and Raabe (2008) developed an analytical model that views bone as transversely isotropic. It considers only Haversian canals as the porous space within the bone microstructure. Another model employing two steps, views the lamellae as open isotropic hydroxyapatite foams. The first part represents the isotropic crystal foam as a 2-phase polycrystal, then it considers the foam as containing spherical, non-specific pores. Helmich and Ulm, 2002 determined an appropriate model to have two main inputs; mineral volume fraction and collagen volume fraction. They went on in 2004 to expand the model to having three volume fraction inputs: hydroxyapatite, collagen, and micropore space (Hellmich et al., 2004). Fritsch et al. (2008) created a continuum mechanics model based on the works of Helmich and Ulm (2002) and Hellmich et al. (2004) that goes beyond porosity and stiffness relationships to resolve the material-immanent microstructures governing the overall mechanical behavior. The effect of biological liquids on mechanical properties of bone is usually taken into account with methods of poroelasticity. Yoon and Cowin (2008b) model the anisotropic poroelastic constants of a single osteon from two perspectives; drained and undrained. The undrained osteon would then have an impact on the poroelasticity from the fluid being compressed within the pores. This model allows one to distinguish between deformation-driven fluid movements (Cowin, 1999; Cowin and Sadegh, 1991) and the effect of liquid bound within closed pores (Hellmich et al., 2009). Deuerling et al. (2009) took three models for three different length scales of bone hierarchy and then applied their crystal orientation.

Many results on the mechanical properties of bone have been obtained using numerical simulations, mostly done using finite element modeling. Hogan (1992) and Crolet et al. (1993) created numerical simulations of the anisotropic moduli of cortical bone, considering only Haversian canals as elements of the porous space. Mullins et al. (2007) considered Haversian canals, Volkman's canals, and osteocyte lacunae as elements of the porous space. Dong and Guo (2004) accounted for transverse-isotropy of the matrix with the porosity associated solely with Haversian canals. Some reasons for these simplifications may be the mathematical difficulties associated with analysis of the inhomogeneities that are arbitrarily oriented in transversely-isotropic material. Despite the success of these models, they neglect potential influences from other pore types even though the contributions to the moduli of other pore types may be very strong (Currey, 1984; Martin and Burr, 1989).

To the best of our knowledge all existing analytical models of cortical bone either consider the dense bone matrix as isotropic, with any anisotropy due to oriented pores only, or they do not include a wide variety of pore type and size and account for Haversian canals only. Bone is a material with evolving microstructure, so when the partial porosities of different types of pores, the shape of these pores, and the mechanical properties of the dense tissue change with age, this lack in broader consideration by the previous works mentioned may become a serious obstacle on the way of practical applications of the micromechanical models. In the present work, we try to fill this gap. First, we account for

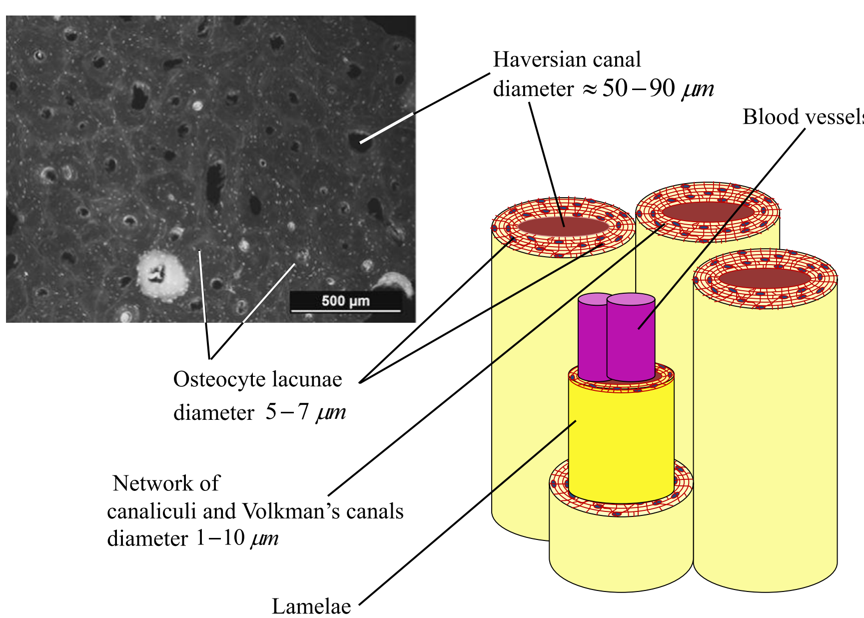

Fig. 1. Microstructure of osteonal cortical bone: SEM photomicrograph (cross-section of longitudinal cortical bovine femur) and the model used for micromechanical analysis.