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Research Paper

The poro-viscoelastic properties of trabecular bone: a micro computed tomography-based finite element study

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ABSTRACT

Bone is a porous structure with a solid phase that contains hydroxyapatite and collagen. Due to its composition, bone is often represented either as a poroelastic or as a viscoelastic material; however, the poro-viscoelastic formulation that allows integrating the effect of both the fluid flow and the collagen on the mechanical response of the tissue, has not been applied yet. The objective of this study was to develop a micro computed tomography (μCT)-based finite element (FE) model of trabecular bone that includes both the poroelastic and the viscoelastic nature of the tissue. Cubes of trabecular bone ($N=25$) from human distal tibia were scanned with μCT and stress relaxation experiments were conducted. The μCT images were the basis for sample specific FE models, and the stress relaxation experiments were simulated applying a poro-viscoelastic formulation. The model considers two scales of the tissue: the intertrabecular pore and the lacunar-canalicular pore scales. Independent viscoelastic and poroelastic models were also developed to determine their contribution to the poro-viscoelastic model. All the experiments exhibited a similar relaxation trend. The average reaction force before relaxation was 9.28×10^2 N (SD $\pm 5.11 \times 10^2$ N), and after relaxation was 4.69×10^2 N (SD $\pm 2.88 \times 10^2$ N). The slope of the regression line between the force before and after relaxation was 1.92 ($R^2=0.96$). The poro-viscoelastic models captured 49% of the variability of the experimental data before relaxation and 33% after relaxation. The relaxation predicted with viscoelastic models was similar to the poro-viscoelastic ones; however, the poroelastic formulation underestimated the reaction force before relaxation. These data suggest that the contribution of viscoelasticity (fluid flow-independent mechanism) to the mechanical response of the tissue is significantly greater than the contribution of the poroelasticity (fluid flow-dependent mechanism).

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1. Introduction

Trabecular bone is a biological tissue with three main hierarchical levels of porosity: At the intertrabecular pore level, the tissue consists of an irregular network of trabeculae with blood and marrow filling the pores; at the lacunar-canalicular pore level, the pores enclose the bone cells (osteocytes) and the interstitial fluid; at the collagen-apatite level, pores with water surround the organic collagen and the inorganic hydroxyapatite (Fritton and Weinbaum, 2009). The hydroxyapatite provides the hardness and the rigidity to the tissue while the collagen provides its toughness (Boskey and Coleman, 2010; Viguet-Carrin et al., 2006). The viscoelasticity of the tissue has been associated with both the layers of intercrystalline water within the extrafibrillar clusters of hydroxyapatite (Eberhardsteiner et al., 2014) and the arrangement of the molecules of collagen and water (Shen et al., 2011). The mechanical stimuli in the marrow and the interstitial fluid are associated with bone adaptation and regeneration (Fritton and Weinbaum, 2009; Gurkan and Akkus, 2008). Due to the porous nature of bone tissue and its intrinsic viscoelasticity, trabecular bone can be characterized as a poro-viscoelastic material. The biphasic poro-viscoelastic formulation was introduced by Mak (1986a) to study the contribution from the intrinsic viscoelasticity of the matrix and the interstitial fluid flow to the apparent viscoelastic behavior of cartilage. This formulation has been used to study cartilage (Mak, 1986a; Mak, 1986b; Setton et al., 1993) and hydrogels for bone tissue engineering (Kalyanam et al., 2009; Noailly et al., 2008; Strange et al., 2013); however, we are not aware of it being applied to bone tissue.

At the intertrabecular pore scale, trabecular bone has been modeled as either as a poroelastic or as a viscoelastic material. The poroelastic theory (Biot, 1941) has been used to study the role of marrow and interstitial fluid flow (Cowin, 1999; Lim and Hong, 1998; Lim and Hong, 2000; Ochoa et al., 1991a, 1991b) and to explain the time-dependent material properties of the tissue (Carter and Hayes, 1977; Hong and Song, 1998; Hong et al., 2001). The poroelastic models assume elasticity in the solid phase, in spite of the inherent viscoelasticity of bone. On the other hand, the viscoelastic formulation has been used in studies of creep (Bowman et al., 1994; Moore et al., 2004) and stress relaxation (Deligianni et al., 1994; Quaglini et al., 2009; Sasaki et al., 1993). Several studies applying the micro-poromechanics principles have been conducted lately with the objective of including the role of the structure at the collagen-apatite pore scale in the mechanical behavior of the bone (Brynk et al., 2011; Eberhardsteiner et al., 2014; Fritsch et al., 2009; Hellmich and Ulm, 2005; Hellmich et al., 2009). Hellmich and Ulm (2005) were able to determine the poroelastic properties of trabecular tissue as a function of the micropore space and the collagen and hydroxyapatite volume fractions. Recently, in order to investigate the mechanical properties of the mineral and the protein phases, Chen and McKittrick (2011) conducted a study of demineralized and deproteinized trabecular bone and showed that removing either the organic or the inorganic material significantly reduced the strength of the tissue.

The mechanical response of trabecular bone depends also on its micro architecture. Recently, bone studies have included the micro architecture of the tissue into finite element (FE) models using micro computed tomography (μCT) images (Müller et al., 1994; van Rietbergen et al., 1998). However, in most of the μCT-based studies, trabecular bone has been characterized as linear elastic or elasto-plastic in order to determine bone strength (Bevill and Keaveny, 2009; Guillén et al., 2011; MacNeil and Boyd, 2008; Sanyal et al., 2012).

Characterization of the mechanical properties of bone tissue is important to fully understand its mechanical behavior, and for the study of the effect of bone-related diseases on the biomechanical response of the tissue. The objective of this study was to develop a μCT-based FE model of trabecular bone at the intertrabecular pore scale that accounts for the poro-viscoelasticity of the tissue. This formulation provides the ability to include the intrinsic viscoelastic response of the bone matrix in addition to the poroelastic nature of the tissue. Validation will be achieved comparing sample specific μCT-based FE models with mechanical tests.

2. Methods

2.1. Mathematical description of the model

The constitutive equations for a linear isotropic poroelastic material can be written as follows (Biot, 1941; Rice and Cleary, 1976):

The constitutive equation for the porous solid is:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \delta_{ij}\left(K - \frac{2G}{3}\right)\varepsilon_{kk} - \delta_{ij}\alpha p \tag{1}$$

where σ_{ij} and ε_{ij} are the stress and strain tensors, p is the pore pressure, K and G are the bulk and the shear moduli, α is the Biot coefficient of effective stress, and δ_{ij} is the Kronecker delta. The Biot coefficient can be expressed as:

$$\alpha = 1 - \frac{K}{K_s} \tag{2}$$

where K_s is the bulk modulus of the solid.

The constitutive equation for the fluid is:

$$\zeta = \alpha\varepsilon_{kk} + \frac{\alpha^2}{K_u - K}p \tag{3}$$

where ζ is the variation of fluid content per unit volume of porous media and K_u is the undrained bulk modulus. The undrained bulk modulus can be expressed as:

$$K_u = K + \frac{\alpha^2 K_s K_f}{\varphi K_s + (\alpha - \varphi)K_f} \tag{4}$$

where φ is the pore volume fraction and K_f is the bulk modulus of the fluid.

The Darcy's law is expressed as:

$$q_i = -\frac{k}{\mu_f}\left(\frac{\partial p}{\partial x_i}\right) \tag{5}$$

where q_i is the rate of fluid volume crossing a unit area of porous solid, k the intrinsic permeability having dimension of length squared and μ_f the fluid viscosity.

The equilibrium equation is defined as:

$$\sum_{i=1}^{3}\frac{\partial \sigma_{ij}}{\partial x_i} = 0 \tag{6}$$