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Fast and accurate specimen-specific simulation of trabecular bone elastic modulus using novel beam–shell finite element models

Jef Vanderoost [a], Siegfried V.N. Jaecques [a], Georges Van der Perre [a], Steven Boonen [b], Jan D'hooge [c], Walter Lauriks [d], G.Harry van Lenthe [a,e,*]

[a] *Division of Biomechanics, Department of Mechanical Engineering, K.U.Leuven, Leuven, Belgium*
[b] *University Center for Metabolic Bone Diseases and Division of Gerontology and Geriatric Medicine, K.U.Leuven, Leuven, Belgium*
[c] *Division of Cardiovascular Imaging and Dynamics, Department of Cardiovascular Diseases, K.U.Leuven, Leuven, Belgium*
[d] *Division of Acoustics and Thermal Physics, Department of Physics and Astronomy, K.U.Leuven, Leuven, Belgium*
[e] *Institute for Biomechanics, ETH Zurich, Zurich, Switzerland*

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Elastic modulus and strength of trabecular bone are negatively affected by osteoporosis and other metabolic bone diseases. Micro-computed tomography-based beam models have been presented as a fast and accurate way to determine bone competence. However, these models are not accurate for trabecular bone specimens with a high number of plate-like trabeculae. Therefore, the aim of this study was to improve this promising methodology by representing plate-like trabeculae in a way that better reflects their mechanical behavior. Using an optimized skeletonization and meshing algorithm, voxel-based models of trabecular bone samples were simplified into a complex structure of rods and plates. Rod-like and plate-like trabeculae were modeled as beam and shell elements, respectively, using local histomorphometric characteristics. To validate our model, apparent elastic modulus was determined from simulated uniaxial elastic compression of 257 cubic samples of trabecular bone (4 mm × 4 mm × 4 mm; 30 μm voxel size; BIOMED I project) in three orthogonal directions using the beam–shell models and using large-scale voxel models that served as the gold standard. Excellent agreement (R^2=0.97) was found between the two, with an average CPU-time reduction factor of 49 for the beam–shell models. In contrast to earlier skeleton-based beam models, the novel beam–shell models predicted elastic modulus values equally well for structures from different skeletal sites. It allows performing detailed parametric analyses that cover the entire spectrum of trabecular bone microstructures.

1. Introduction

Elastic modulus and strength of bones are negatively affected by a number of metabolic bone diseases, in particular osteoporosis. Evidence from prospective studies, using markers of bone formation and bone resorption, indicates that an excessive rate of bone remodeling is one of the major determinants of age-related bone loss and osteoporosis (Bauer et al., 1999; Cummings et al., 1993; Garnero et al., 1996). Excessive bone remodeling leads to changes in microarchitecture with accumulation of microdamage and some degree of hypomineralization (Mori et al., 1997), resulting in bone fragility.

Experimental mechanical tests are considered the gold standard to determine bone competence and have been performed extensively to quantify the effects of osteoporosis and of potential treatments. But these tests have practical limitations and a high sensitivity to measurement errors (Keaveny et al., 1997).

Elastic moduli can be derived accurately from micro-computed tomography (μCT)-based voxel-FE (μFE) models that mimic the microstructure of the bone in detail by representing every voxel as a hexahedral element (Van Rietbergen et al., 1995). These models are necessarily large to capture the complex architecture and thus are computationally demanding, especially in nonlinear analysis. Furthermore, even though these models incorporate the intricate trabecular architecture, the structure–mechanics relationships remain unclear. One reason is that these models are not readily manipulated to independently test the influence of different local structural properties.

Beam FE models have been proposed as an alternative to μFE analyses (Pothuaud et al., 2004; Stauber et al., 2004; van Lenthe et al., 2006). Typically, these models represent trabecular bone as a three-dimensional (3D) network of beams. Beam properties are derived from local analyses of the individual trabeculae. These models have the advantage that they require far less CPU-time

* Corresponding author at: Division of Biomechanics, Department of Mechanical Engineering, Celestijnenlaan 300C b2419, 3001 Leuven, Belgium.
Tel.: +32 16 32 25 95.
E-mail address: harry.vanlenthe@mech.kuleuven.be (G.Harr. van Lenthe).

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