available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jmbbm

ELSEVIER

Research paper

Multiscale FE method for analysis of bone micro-structures

L. Podshivalov[a,b,*], *A. Fischer*[a], *P.Z. Bar-Yoseph*[b]

[a] *Laboratory for CAD and Life Cycle Engineering, Faculty of Mechanical Engineering, Technion, Israel*
[b] *Computational Biomechanics Laboratory, Faculty of Mechanical Engineering, Technion, Israel*

ARTICLE INFO

Article history:
Published online 9 March 2011

Keywords:
Bone micro-structure
μCT/μMRI images
Multiscale
Diagnostic system

ABSTRACT

Bones are composed of hierarchical bio-composite materials characterized by complex multiscale structural geometry and behavior. The architecture and the mechanical properties of bone tissue differ at each level of hierarchy. Thus, a multiscale approach for mechanical analysis of bone is imperative.

This paper proposes a new approach for 3D multiscale finite element analysis of trabecular bone that can offer physicians a "digital magnifying glass" to facilitate continuous transition between macro- and micro-scales. The approach imitates the human ability to perceive details. That is, zooming-out from an object causes fewer details to be visible. As a result, the material appears to be smoother and more homogeneous. Zooming-in, in contrast, reveals additional details and material heterogeneity.

Realization of the proposed approach requires synergy between a hierarchical geometric model for representing intermediate scales and a mechanical model for local material properties of bone tissue for each scale. The geometric model facilitates seamless and continuous bi-directional transition between macro- and micro-scales, while the mechanical model preserves the effective material properties.

A 2D model of a simplified trabecular structure was implemented and analyzed in order to assess the feasibility of the proposed multiscale approach. The successful results of this model led to extending the method into 3D and analyzing real trabecular structures.

1. Introduction

Bone is a hierarchical material whose architecture differs at each level of hierarchy and whose mechanical properties can vary considerably, even on the same specimen, due to bone heterogeneity. Thus, a multiscale approach seems to be a natural methodology for geometric modeling and mechanical analysis of bone (Knothe Tate, 2007).

Currently, Bone Mineral Density (BMD) testing is used for diagnosing osteoporosis (Kanis et al., 2008; Qaseem et al., 2008), but it accounts for only 70% of bone strength (Draper et al., 2005; Lane, 2006). Because of the difficulty in accurate measurement and in standardization of instruments and sites, experts are in dispute over the continued use of this diagnostic criterion, which occasionally fails to diagnose patients with increased risk of osteoporotic fractures (Schuit et al., 2004). These facts have led to the need to develop 3D micro-scale scanning methods from which 3D models can be constructed and then used for bone micro-structural analysis.

* *Corresponding author at:* Laboratory for CAD and Life Cycle Engineering, Faculty of Mechanical Engineering, Technion, Israel. Tel.: +972 4 8292334; fax: +972 4 8295711.
E-mail address: slpod@technion.ac.il (L. Podshivalov).

1751-6161/$ - see front matter
doi:10.1016/j.jmbbm.2011.03.003

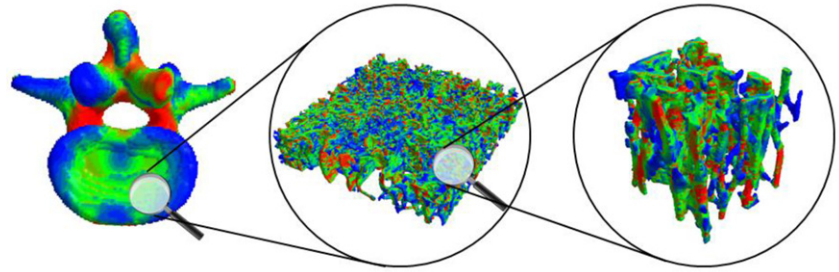

Fig. 1 – Continuous multiscale approach: macro-scale, meso-scale and micro-scale.

Recent improvements in 3D imaging technology allow *in-vivo* and *in-vitro* 3D high-resolution scanning and reconstruction of large specimens or even of whole bone models. These methods are: (a) peripheral Quantitative Computed Tomography (pQCT); (b) micro Computed Tomography (μCT); and (c) micro Magnetic Resonance Imaging (μMRI). All these methods are based on the proven technology of CT and MRI. They did not become available earlier, mostly due to technological immaturity and the absence of appropriate computational resources (Van Rietbergen, 2001). Furthermore, a new set of 3D structural and topological parameters has been established to evaluate structural and mechanical properties of reconstructed 3D samples (Odgaard, 1997). Therefore, the technology and the algorithms necessary to replace the 2D methods for estimating strength of bone micro-structure with a real 3D virtual biopsy system already exist today. Moreover, with the constant increase in computational power of a single CPU and the development of multi-core chips, most algorithms can be executed without the need for clusters or supercomputers. However, current medical applications are limited to the size of biopsy.

Multiscale modeling and FE analysis

Multiscale FE analysis, now on the cutting edge of biomedical research worldwide, facilitates computerized multi-structural analysis. Multiscale finite element analysis is essential for efficient and reliable mechanical analysis of bone structure. Most state-of-the-art multiscale methods utilize multi-step homogenization (Fritsch et al., 2009; Hellmich et al., 2004; Nikolov and Raabe, 2008) or mesh superposition (Kawagai et al., 2006). These methods assume order-of-magnitude scale separation between two consecutive levels of hierarchy. Therefore, continuous transition in terms of geometrical modeling and mechanical properties is not available. In this paper, the current discontinuous representation of the multiscale model is referred to as binary modeling, in which no intermediate scales are represented.

In this paper, a new approach to multiscale finite element mechanical analysis of trabecular bone is proposed. Using this approach, physicians can employ a "*digital magnifying glass*" that provides continuous transition between macro- and micro- scales by imitating the human perception of details. Zooming-out from the object makes fewer details visible. As a result, the material appears to be smoother and more homogeneous. On the other hand, zooming-in reveals additional details and material heterogeneity, as depicted in Fig. 1.

Two important components in the continuous computational multiscale model are: (a) the hierarchical geometric model for representing each intermediate scale, and (b) the local material properties model for each scale.

The hierarchical geometric model begins with model reconstruction from μCT/μMRI images and represents a critical stage in the process, since a low quality 3D reconstruction can lead to incorrect analysis results and eventually to a wrong diagnosis. While a full examination of model reconstruction is beyond the scope of this paper, we note that a common approach to 3D model generation from medical images is to convert pixels directly into hexahedron elements (voxels). This approach is widely used by the biomedical community for μFE analysis of bone micro-structure (Arbenz et al., 2010; Rincón-Kohli and Zysset, 2009; Van Lenthe et al., 2008; Van Rietbergen, 2001), despite its disadvantage in the form of jagged edges on the envelope. A smoothing algorithm for this type of elements was proposed in Boyd and Müller (2006). A different approach, based on surface and volumetric reconstruction (Azernikov and Fischer, 2006; Miropolsky and Fischer, 2009) or voxelization (Morris, 2007), where voxels are extracted directly from surface mesh. In this work, we have used the voxel approach for reconstructing the hexahedron model at the micro-scale structural level.

The literature discusses a variety of analytical models that can be used for continuous estimation of effective elastic constants of composite materials. Among the most known methods are the percolation theory (Phani and Niyogi, 1987), the Mori–Tanaka method (Mori and Tanaka, 1973), the self-consistent method (Hill, 1965) and Eshelby's inclusion method (Eshelby, 1957). Yet all these methods make certain assumptions regarding the shape, the distribution and the distance between the inclusions (Qu and Cherkaoui, 2007). In most of the methods, the shape is assumed to be spherical or ellipsoidal. Some methods can only treat materials characterized by no interactions between the inclusions. Transition from an inclusion to a void is not trivial. Some of the above methods cannot accurately predict the effective material properties when inclusions are replaced by voids. Therefore, in this paper we propose a new method for evaluation of local material properties at each intermediate level to overcome limitations of the existing methods.

Integrating these modules creates a multiscale computational model that can serve as the basis for a reliable