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A comparison of enhanced continuum FE with micro FE models of human vertebral bodies ☆

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ABSTRACT

Continuum finite element (FE) models are standard tools for determination of biomechanical properties of bones and bone-implant systems. This study investigates the accuracy of an enhanced continuum FE model by taking μFE as the gold standard. The enhanced continuum models account for trabecular bone morphology (density and fabric) as well as for an anatomically correct cortical shell. Vertebral body slice models are extracted from high-resolution CT images using an algorithm proposed in [Pahr and Zysset, 2008b. From high-resolution CT data to FE models: development of an integrated modular framework. Computer Methods in Biomechanics and Biomedical Engineering, in press.]. Three different models are generated: the proposed enhanced density-fabric-based model with a subject-specific cortex and two classical isotropic density-only models, with and without explicit modeling of the cortical shell. The material property errors of the used morphology-elasticity relationship are minimized by using elasticity tensors from 60 cubical μFE models which are cropped from the trabecular centrums of the investigated vertebral bodies. Two different boundary conditions—kinematic [Van Rietbergen et al., 1995. A new method to determine trabecular bone elastic properties and loading using micromechanical FE models. Journal of Biomechanics 28 (1), 69–81] and mixed [Pahr, D.H., Zysset, P.K., 2008a. Influence of boundary conditions on computed apparent elastic properties of cancellous bone. Biomechanics and Modeling in Mechanobiology 7, 463–476.]—are used in these FE models. After removal of the endplates, compressive and antero–posterior shear loading is applied on the investigated vertebral bodies. Individual error sources are studied in more detail by loading also the trabecular centrum (removed shell) and the cortical shell alone. It is found that the cortex-only models need a correction of the shell thickness when transforming from a voxel to a smooth description. The trabecular centrum alone gives too stiff and too soft a response using material calibration with kinematic and mixed boundary conditions, respectively. A comparison of the whole vertebral body stiffnesses shows that an orthotropic cancellous bone material calibrated with kinematic boundary conditions corresponds best with μFE. Taken together, the proposed enhanced homogenized surface-based FE model is structurally more accurate than density-only models.

1. Introduction

Patient-specific continuum finite element (FE) models of vertebral bodies based on clinical quantitative computer tomography (QCT) images become increasingly attractive for evaluation of stiffness and strength *in vivo* (Faulkner et al., 1991; Crawford et al., 2003; Liebschner et al., 2003; Imai et al., 2006; Chevalier et al., 2008). Even damage susceptibility of specific human vertebral bodies for instance along the course of anti-resorbtive or anabolic treatments can be modeled (Keaveny et al., 2007; Graeff et al., 2007). Segmentation of the QCT images together with volume meshing provide the FE models. The stiffness of the individual finite elements in the spongious bone region. is related to calibrated mineral densities obtained from the QCT image (density-only). At these clinical resolutions, the cortical shell including the endplates cannot be properly segmented and the trabecular morphology beyond density remains invisible. Despite proper experimental calibration and the undeniable value of these continuum FE models, questions rise how their accuracy is affected by the lack of a subject-specific cortex and trabecular bone fabric.

In the laboratory, micro finite element (μFE) models based on high-resolution computer tomography (μCT or HR-pQCT) represent the current gold standard to investigate the stiffness of human vertebral bodies *in vitro* (Homminga et al., 2004; Eswaran et al., 2007). In such models, the CT voxel information is converted

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directly into 8-noded hexahedral elements, which result in large numbers of degrees of freedom. The bone tissue is assumed to be isotropic and the elastic parameters are typically taken from micro-indentations measurements. These μFE models include the cortex and account naturally for bone morphology but require large computing resources.

In awareness of the limitations of current modeling approaches, we propose an enhanced continuum FE model based on high-resolution CT images which includes an anatomy-specific cortex and accounts for bone morphology by using fabric–elasticity relationships (Cowin, 1985; Zysset, 2003). This hybrid approach might be more robust than μFE at intermediary CT image resolutions, requires less computing resources, is easily extendable to non-linear behavior and converges naturally to the density-only modeling for low clinical resolutions.

The main aim of this work is to investigate the accuracy of such an enhanced continuum FE model based on HR-pQCT. The elastic structural response of human vertebral body slices is predicted by taking μFE based on the same HR-pQCT images as the gold standard. Taking μFE as the gold standard avoids experimental errors and allows us to consider two sources of errors: (1) modeling of a smooth cortex, (2) the morphology–elasticity relationship necessary for assigning the trabecular bone properties. Additionally, the predictions of density-only models are compared to the enhanced model predictions.

We hypothesize that, unlike the models including a simple density-only morphology–elasticity relationship, the enhanced continuum FE model including both an anatomy-specific cortex modeling and a fabric–elasticity relationship for trabecular bone makes the closest structural predictions to those of μFE models.

In this study, we use slices of vertebral bodies from HR-pQCT scans (similar to Eswaran et al., 2007) with a resolution of 82 μm. In the first step, the error of extracting a smooth anatomical cortex is investigated by considering FE models of the isolated cortical shell alone. The errors due to the morphology–elasticity relationship were minimized *a priori* by calibrating them with virtual material tests of 60 cubical micro FE models cropped from the same vertebral bodies ("best case scenario"). Due to their significant impact on the homogenization results (Pahr and Zysset, 2008a), two types of boundary conditions are used: kinematic uniform boundary conditions (KUBC, Van Rietbergen et al., 1996) and periodicity compatible mixed uniform boundary conditions (PMUBC, Pahr and Zysset, 2008a). To quantify the errors due to the density-only and density-fabric-based morphology–elasticity relationship, we focused on the stiffness of the trabecular centrum alone. In the third step we compared the stiffness of the whole vertebral body slices for axial compression and antero–posterior shear loading.

2. Methods

2.1. CT-scanning

Twelve vertebral bodies were extracted from four human lumbar spines (spine/level/gender/age: A/L2-L4/M/47; B/L1-L5/M/70; C/L4-L5/M/66; D/L4-L5/M/83) and scanned individually in a water-filled container with a high-resolution pQCT system (XtremeCT, 82 μm isotropic resolution, 59.4 kV, 1000 μA, Scanco Medical AG, Brüttisellen, Switzerland) to provide a three-dimensional map of bone mineral density across the vertebral bodies. Details of the scanning procedure can be found in Chevalier et al. (2006, 2008).

2.2. μFE models

The main model generation steps are illustrated in Fig. 1. Segmentation and meshing were based on a fully automated algorithm (Pahr and Zysset, 2008b). Details are provided in Appendix A. After segmentation all images were cropped (constant slice thickness of 17.22 mm) such that the endplates were totally removed.

The μCT voxels were directly converted to isotropic hexahedral FEs ($E = 20\,000$ MPa and $\nu = 0.3$). Three geometric model types were generated: the whole vertebral body, the trabecular centrum, and the cortex (Fig. 1 middle bottom). Constant displacements were applied along the superior–inferior axis (compression) and along anterior–posterior axis (shear loading), respectively. ParFE (Arbenz et al., 2006; Mennel and Sala, 2007) was used for the μFE analyses and run on a server with 2 × 2 Xeon 5160 CPUs and 64 GByte RAM.

2.3. Enhanced continuum FE models

All continuum FE models were generated with a fully automated algorithm proposed by Pahr and Zysset (2008b) (for details see Appendix A). During the transition from a digital to a smooth volume representation "digitization errors" occur which had to be corrected (see Pahr and Zysset, 2008b). Different cortical shell thickness corrections were investigated—no correction, mechanically consistent, and volume preserving correction. An estimate for a mechanically consistent correction was found by considerations similar to Guldberg et al.

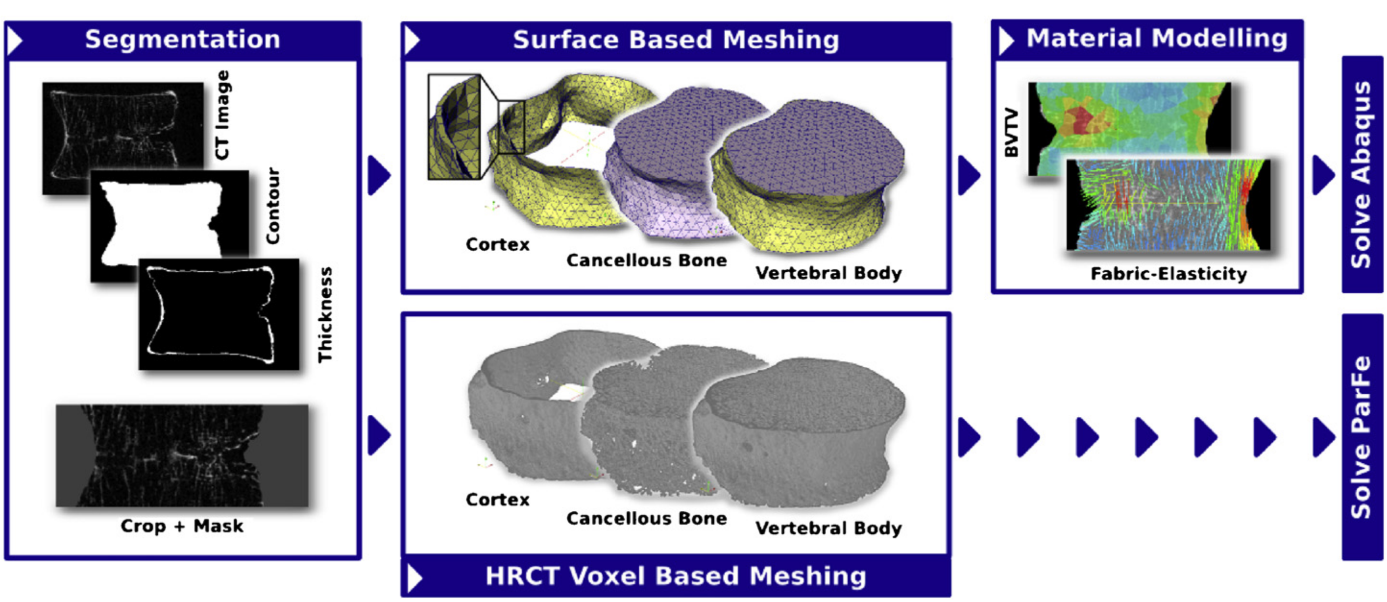

Fig. 1. From CT-data to FEM results. Overview of analysis steps done during study.