Technical note

Introduction and evaluation of a gray-value voxel conversion technique

Jasper Homminga\textsuperscript{a,b}, Rik Huiskes\textsuperscript{a,c}, Bert Van Rietbergen\textsuperscript{c}, Peter Ruegsegger\textsuperscript{d}, Harrie Weinans\textsuperscript{b,*}

\textsuperscript{a}Orthopedic Research Laboratory, University of Nijmegen, Netherlands
\textsuperscript{b}Erasmus Orthopedic Research Laboratory, EE1614 Erasmus University, Rotterdam, P.O. Box 1738, 3000-DR Rotterdam, Netherlands
\textsuperscript{c}Faculty of Biomedical Engineering, Eindhoven University of Technology, Netherlands
\textsuperscript{d}Institute for Biomedical Engineering, Swiss Federal Institute of Technology, Switzerland

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Abstract

In micro finite element analyses (\textmu FEA) of cancellous bone, the 3D-imaging data that the FEA-models are based on, contain a range of gray-values. In the construction of the eventual FEA-model, these gray-values are commonly thresholded. Although thresholding is successful at small voxel sizes, at larger voxel sizes there is substantial loss of trabecular connectivity. We propose a new method: the gray-value method, where the \textmu FEA-models use the information within the 3D-imaging data directly, without prior thresholding. Our question was twofold. First, how does the gray-value method compare to both plain and mass-compensated thresholding? Second, what is the effect of element size on the results obtained with the gray-value method? We used nine \textmu CT-scans of human vertebral cancellous bone. These were degraded to represent different resolutions, and converted into \textmu FEA-models using plain thresholding, mass-compensated thresholding, and the gray-value method. The apparent elastic moduli of the specimens were determined using \textmu FEA. The different methods were compared on the basis of the apparent elastic moduli, compared to those calculated for a 28 \textmu m reference model. The results showed that the gray-value method greatly improves the results relative to other methods. The gray-value method gives accurate predictions of the apparent elastic moduli, for voxel sizes up to one trabecular thickness (Tb.Th.). For voxel sizes greater than one Tb.Th. the accuracy, although still better than for both thresholding methods, becomes increasingly worse.

Keywords: Finite element analysis; Cancellous bone; Micro-imaging; Mechanical properties; Gray-value technique

1. Introduction

The apparent elastic properties of cancellous bone depend on the volume fraction, the architecture, and the elastic tissue properties of the mineralized matrix. 3D-reconstruction from micro-imaging techniques can be used as the basis for \textmu FEA models (Fyhrie et al., 1992; Hollister and Kikuchi, 1992; van-Rietbergen et al., 1996a).

The 3D-reconstructions, as obtained with \textmu CT (Ruegsegger et al., 1996) or \textmu MRI (Majumdar and Genant, 1997), contain a range of gray-values. There are a number of causes for this range of values, such as differences in the degree of mineralization of the bone material and noise. However, the most important cause is the partial volume effect. Even though the resolution of these micro-techniques is high, it is limited; a voxel may contain bone and marrow (rather than just bone or marrow). Usually, before the 3D-reconstructions are turned into \textmu FEA-models, they are binarized into bone and marrow, using some method of thresholding. With these thresholding methods only voxels with gray-values above a certain threshold are considered bone whereas all others are considered marrow. A plain thresholding method ensures the best possible agreement between the volume fraction before and after thresholding (Ulrich et al., 1998). At small voxel sizes (high resolutions), plain thresholding yields good results (Fig. 1). At larger voxel sizes (lower resolutions) there is a substantial loss of trabecular connections, resulting in unconnected bone.
parts (Fig. 2). Ulrich et al. (1998) introduced mass-compensated thresholding, a method that ensures the best possible agreement between the volume fraction before thresholding and that of the µFEA-model with all unconnected parts removed from the mesh. At larger voxel sizes, mass-compensated thresholding yields better results than plain thresholding. One remaining problem is that mass-compensated thresholding tends to compensate for the unconnected parts by thickening the remaining structure (Fig. 2). The problems with both the plain- and the mass-compensated thresholding methods originate from the fact that they are thresholding methods, which by definition, result in a loss of information from the raw 3D-reconstructions. Thresholding uses the gray-values of the voxels only in the differentiation between bone and marrow. This led us to hypothesize that it may be better to use these gray-values to scale the tissue moduli in the µFEA-model. With this method, the µFEA-models use the information within the 3D-reconstructions directly, without prior thresholding (Fig. 2). The µFEA-models made with this method contain not only bone and marrow elements, but also partial volume elements. The gray-values of the elements are then used to scale the tissue moduli.

The question for the present study was twofold. First, how does the gray-value method compare to both plain and mass-compensated thresholding? Second, what is the effect of element size on the results obtained with the gray-value method?

2. Methods

We used nine 3D-reconstructions of 4mm³ human vertebral cancellous bone cubes (µCT20, Scanco...
Medical, 3D-resolution: 28 μm, 3D-voxel size: 14 μm, Ruegsegger et al., 1996). We considered the binarized 14 μm voxel meshes as idealized structures, free of differences in mineralization. These structures were then degraded (coarsened) to represent the result of different resolutions, simulating an ideal scanner, free of beam-hardening or noise. In the degradation, the gray-value of the degraded voxel represented the ratio of underlying tissue modulus, E tissue, where G V element is the relative gray-value of the element set in a range from 0 (marrow) to 1 (bone), and γ represents the underlying architecture of the element (Gibson, 1985). The value of G V was taken as 5 GPa (Hou et al., 1998; Ladd et al., 1998; van-Rietbergen et al., 1995). The apparent elastic moduli of the specimens were determined using μFEA (van-Rietbergen et al., 1996b). The apparent elastic moduli for the 28 μm μFEA-models were used as our reference values, the ‘gold standard’.

In the first part of the study, we compared the plain and mass-compensated thresholding, and the gray-value methods. To this end we generated three voxel meshes per specimen, with voxel sizes of 112 μm, which was in the order of the average trabecular thickness. The μFEA-models were generated from the 112 μm-voxel meshes using the three different methods, plain thresholding, mass-compensated thresholding, and the gray-value method (Fig. 2). All elements were given linear elastic, isotropic material properties with a Poisson’s ratio of 0.3 and an elastic modulus of 5 GPa (Hou et al., 1998; Ladd et al., 1998; van-Rietbergen et al., 1995). The effects of different voxel sizes were evaluated by the calculated apparent elastic moduli, compared to the apparent elastic moduli calculated for the 28 μm reference model, the ‘gold standard’.

### 3. Results

#### 3.1. Comparison of the three methods

For element sizes in the order of the trabecular thickness, using mass-compensated thresholding rather than plain thresholding substantially reduced both the mean and the range of the deviation from baseline values for the volume fraction and all apparent elastic moduli (Fig. 3). Using the gray-value method gave a further improvement for the volume fraction and all the apparent elastic moduli, particularly in the range of the deviation (Fig. 3).

#### 3.2. Effect of voxel size (resolution) on the gray-value method

Using the gray-value method, the transverse moduli increased with increasing voxel size. For voxel sizes less

![Range and mean deviation from baseline [%]](image)

Fig. 3. Mean and range of the deviation from baseline values for the different methods, at element sizes on the order of the trabecular thickness. White for threshold without mass compensation, black for threshold with mass compensation, and gray for the gray-value method. Plain thresholding resulted in loss of volume fraction and substantial changes in the apparent elastic moduli. Both mass-compensated thresholding and the gray-value method showed almost no change in volume fraction, and only small changes in the apparent elastic moduli. Overall the changes in the apparent elastic moduli are smaller with the gray-value method than with mass-compensated thresholding, particularly the range of the deviation-values is much smaller.

![Image](image)

where, E element is the element elastic modulus, E tissue is the tissue modulus, G V element is the relative gray-value of the element set in a range from 0 (marrow) to 1 (bone), and γ represents the underlying architecture of the element (Gibson, 1985). The value of E tissue was taken as 5 GPa (Hou et al., 1998; Ladd et al., 1998; van-Rietbergen et al., 1995) and the value of γ was set at 1.5. From a pilot study (Homminga et al., 1998) we found that this gamma gave the best agreement between the gray-value models and the ‘gold standard’ models. The apparent elastic moduli of the specimens were determined using μFEA (van-Rietbergen et al., 1996b). The different methods were compared on the basis of the calculated apparent elastic moduli. Specifically, on the basis of the deviations from the apparent elastic moduli calculated for the 28 μm baseline model, the ‘gold standard’.

In the second part of this study, we evaluated the effects of voxel size on the apparent elastic moduli, using the gray-value technique. To this end, we created seven voxel meshes/specimen, with voxel sizes increasing from 56 to 980 μm all using the gray-value method. All elements were given linear elastic, isotropic material properties with a Poisson’s ratio of 0.3 and an elastic modulus based on the gray-value of the element (Eq. (1)). The apparent elastic moduli of the specimens were compared to the apparent elastic moduli calculated for the 28 μm reference model, the ‘gold standard’.
trabecular bone can be accurately estimated with a FEA-model. In order to predict the elastic properties of the trabecular architecture and the volume fraction are adequately represented in the models, but the trabecular thickness, we feel that the results are meaningful for other anatomical sites as well. Second, the gray-value method requires a value for the power (γ, Eq. (1)) in the relationship between the element gray-value and the element elastic modulus (Gibson, 1985). From a pilot study (Homminga et al., 1998) we found that a value of 1.5 gave the best agreement with reference values from our ‘gold standard’ models. Increasing the gamma value to 1.6 changed the mean deviation for the average apparent elastic modulus from 1 to 5% (voxel sizes \( \approx 1 \times \text{Tb.Th.} \)). The effects will clearly be much smaller for the finer models. As the exact relationship between the element gray-value and the element elastic modulus is presently not available for sites other than the lumbar vertebrae, this is a clear disadvantage of the gray-value method compared to the thresholding methods, where a BMD measurement can be used to find the correct threshold. Third, we used binarized \( 14\mu m \) voxel meshes as our underlying structures, which were then degraded to coarser resolutions. As a result of this, partial volume effects are the only factor in the models. Factors like noise, beam-hardening, the presence of different types of marrow (e.g. fat content), or differences in tissue mineralization will likely complicate matters. Our results thus represent the upper limit for the accuracy that can be achieved in reality. Fourth, in order to obtain accurate tissue level stresses and strains at least 4–5 elements are required over the diameter of a trabecula (Charras and Guldberg, 2000, Niebur et al., 1999). At larger voxel sizes, neither the gray-value method nor the thresholding methods yield accurate stresses and strains at the tissue level. Through its better prediction of the apparent elastic moduli, the gray-value method will also give a better prediction of the strain distribution. The tissue stresses, however, will not be accurate because the Young’s moduli of the gray elements are based on a partial volume criterion.

In conclusion, the mass compensating thresholding method greatly improves upon the plain thresholding method, but the accuracy can be further improved by a FEA-model. These are models that

4. Discussion

At small voxel sizes \( (<0.5\times \text{Tb.Th.}) \), all models have more than 4–6 elements covering the cross-section of a typical trabecula; there are only a few partial volume elements. With these voxel sizes both the trabecular architecture and the volume fraction are adequately represented in the \( \mu \)FEA-models. These are models that adequately represent the modes of deformation that occur in real trabecular bone samples, resulting in accurate approximations of the actual apparent elastic moduli (Fig. 4).

At larger voxel sizes \( (>0.5\times \text{Tb.Th.}) \), there is an increasing number of partial volume elements. With these voxel sizes the volume fraction is still adequately represented in the models, but the trabecular architecture is increasing under-represented. The models no longer adequately represent the true modes of deformation. In order to predict the elastic properties of the model, it becomes more and more important to account for local elastic properties (Fig. 4).

It has been shown that the elastic properties of trabecular bone can be accurately estimated with \( \mu \)FEA models that use isotropic tissue elastic properties (Kabel et al., 1999; Keaveny et al., 1998; Ulrich et al., 1997; van-Rietbergen et al., 1995). Hence, the anisotropy in the apparent elastic properties is a result of the anisotropy in the architecture, not of the anisotropy in the tissue elastic properties. With increasing voxel sizes the accuracy of the representation of the trabecular architecture decreases. As a result, the accuracy of the anisotropy in the apparent elastic properties will also decrease. Although outside the scope of this study, this loss of accuracy in the anisotropy could potentially be compensated for by introducing anisotropy in the tissue elastic properties.

Some aspects of the present study must be discussed. First, all the samples that we used in this study were taken from one anatomical site (lumbar vertebrae). However, as all results were considered relative to the trabecular thickness, we feel that the results are meaningful for other anatomical sites as well.
using the gray-value method. For voxel sizes up to one Tb.Th., the gray-value method gives good predictions of the apparent moduli. For voxel sizes larger than one Tb.Th. the predictions become increasingly worse.

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