Complete assessment of elastic properties of trabecular bone architecture from 3D reconstruction images

Citation for published version (APA):
Rietbergen, van, B., Odgaard, A., Kabel, J., & Huiskes, H. W. J. (1997). Complete assessment of elastic properties of trabecular bone architecture from 3D reconstruction images. In H. Boom, C. Robinson, W. Rutten, M. Neuman, & H. Wijkstra (Eds.), *Proceedings of the 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. `Bridging Disciplines for Biomedicine'* (pp. 491-492). Institute of Electrical and Electronics Engineers.

Document status and date:
Published: 01/01/1997

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Amsterdam 1996
2.6.2: Clinical Biomechanics

COMPLETE ASSESSMENT OF ELASTIC PROPERTIES OF TRABECULAR BONE ARCHITECTURE FROM 3D RECONSTRUCTION IMAGES

B. Van Rietbergen, A. Odgaard*, J. Kabel* and R. Huiskes.

Biomechanics Section, Institute of Orthopaedics, University of Nijmegen, P.O.Box 9101, 6500 HB, Nijmegen, The Netherlands E-mail: ortho_sec@mc01.azn.nl
* Biomechanics Laboratory, Dept. of Orthopaedic Surgery, Aarhus University Hospital, Randersvej 1 DK-8200 Aarhus, Denmark. E-mail: anders@ull.biomeklab.aau.dk

Abstract

A method is presented that allows for a complete mechanical evaluation of trabecular bone architecture directly from three-dimensional computer reconstruction images. With this method, the reconstruction images are used as a basis for microstructural FE-analyses. From the results of these analyses the full stiffness matrix of bone specimens is obtained, using a standard mechanics approach. An optimization procedure is then used to find the best orthotropic representation and principal directions of this matrix. The method is demonstrated here relative to two trabecular bone specimens. With the development of *in vivo* reconstructions and the methods demonstrated here, even *in vivo* measurements will be possible.

Introduction

Three-dimensional computer reconstructions of trabecular bone architecture have been introduced as an accurate basis for the determination of three-dimensional morphological parameters. For the study of the mechanical quality of trabecular bone however, mechanical rather than morphological parameters of trabecular architecture are needed. Mechanical parameters can not be accurately determined from morphological parameters since, as yet, no accurate and complete relationships exists between both. Recently, it has been demonstrated that it is possible to find mechanical parameters of trabecular bone directly from microstructural FE-models of bone specimens which are created from three-dimensional computer reconstructions [1,2]. With these FE-models, the mechanical properties of the bone specimen can be obtained by simulating compression test experiments. However, there are a number of problems with the determination of trabecular bone elastic properties in this way. First, only a limited number of elastic constants can be measured. Second, as with real compression test experiments, boundary artifacts can seriously affect the results. Third, extra information on trabecular architecture is needed to find the mechanical main directions. In the present study an alternative method based on high-resolution computer reconstructions of trabecular bone specimens in combination with a standard mechanics FE-approach is presented, that allows for the determination of all orthotropic elastic constants and principal mechanical directions of bone specimens without the need for additional fabric measurements.

Methods

Two trabecular bone specimens of 10 mm each were cut from a whale vertebral body. The first specimen was cut such that its sides were aligned with the vertebral body longitudinal axis, the second specimen such that its sides were rotated 45 degrees relative to this axis.

The morphology of each specimen was digitized in a serial sectioning procedure [3]. The voxel data sets obtained from this procedure were used to create microstructural FE-models by directly converting bone voxels to 8-node brick elements that measure 80 microns on each side (Fig. 1). The resulting FE-models consisted of 566,967 and 653,533 elements for the first and second model respectively.

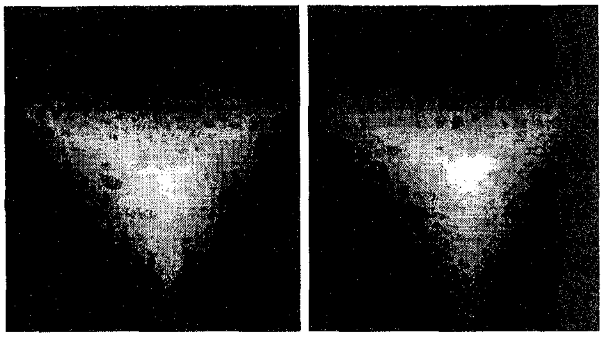

Fig. 1 The FE-models of the two specimens.

Based on an earlier study, all elements were given a linear elastic and isotropic Young's modulus of 5.33 GPa [2]. A special purpose FE-code was used to solve these large FE-problems [4]. Six FE-analyses were needed to calculate the overall (or apparent) material properties of a specimen, as characterized by the stiffness tensor, using a standard mechanics approach [5]. In this way all 21 elastic coefficients in the overall stiffness matrix of the specimen were obtained, while the effects of boundary artifacts is

0-7803-3811-1/97/$10.00 ©IEEE

reduced. An optimization procedure was then used to find the coordinate transformation that yields the best orthotropic representation of this matrix. This procedure makes use of the fact that for orthotropic materials some of the off-diagonal entries in the stiffness matrix are zero when measurement and orthotropy axes are aligned. The best orthotropic representation was obtained by setting these entries to zero after a matrix coordinate transformation that minimizes the square-sum of these entries.

Results

With the methods provided here, the stiffness matrices and mechanical principal directions of both specimens were obtained (Fig. 2). The mechanical main direction was found to align with the vertebra longitudinal direction for both specimens. It was found that the material behavior of both specimens was well described as orthotropic.

Specimen 1:

$$\begin{bmatrix} 791.2 & 360.9 & 318.6 & 1.1 & 5.4 & -0.6 \\ 360.9 & 852.9 & 328.1 & 0.9 & -2.5 & -4.2 \\ 318.6 & 328.1 & 1473.0 & -2.4 & 16.9 & 0.6 \\ 1.1 & 0.9 & 2.4 & 358.7 & 0.5 & 5.1 \\ 5.4 & -2.5 & 16.9 & 0.5 & 344.8 & -0.7 \\ -0.6 & -4.2 & 0.6 & 5.1 & -0.7 & 230.4 \end{bmatrix} \Rightarrow \begin{bmatrix} 791.1 & 360.6 & 318.3 & 1.0 & -2.1 & 1.3 \\ 360.6 & 853.8 & 327.9 & 1.5 & -1.2 & -2.1 \\ 318.3 & 327.9 & 1474.3 & -0.5 & 0.7 & 1.3 \\ 1.0 & 1.5 & -0.5 & 358.8 & 1.5 & 0.7 \\ -2.1 & -1.2 & 0.7 & 1.5 & 344.4 & -0.1 \\ 1.3 & -2.1 & 1.3 & 0.7 & -0.1 & 229.7 \end{bmatrix}$$

Specimen 2:

$$\begin{bmatrix} 698.3 & 281.6 & 284.5 & 8.0 & -0.7 & 11.4 \\ 281.6 & 896.7 & 322.7 & -162.3 & -3.2 & 16.0 \\ 284.5 & 322.7 & 916.0 & -162.2 & -7.2 & 2.4 \\ 8.0 & -162.3 & -162.2 & 348.9 & 10.5 & -9.8 \\ -0.7 & -3.2 & -7.2 & 10.5 & 242.6 & -64.4 \\ 11.4 & 16.0 & 2.4 & -9.8 & -64.4 & 237.8 \end{bmatrix} \Rightarrow \begin{bmatrix} 636.7 & 291.3 & 264.8 & 2.7 & 1.5 & 3.0 \\ 291.3 & 699.8 & 274.5 & 2.7 & 1.3 & -0.8 \\ 264.8 & 274.5 & 1290.9 & -1.1 & -0.9 & 0.9 \\ 2.7 & 2.7 & -1.1 & 304.4 & 1.7 & 0.8 \\ 1.5 & 1.3 & -0.9 & 1.7 & 291.4 & 0.4 \\ 3.0 & -0.8 & 0.9 & 0.8 & 0.4 & 175.4 \end{bmatrix}$$

Fig. 2 The stiffness matrices for specimen 1 (top) and 2 (bottom) in the specimen coordinate system (left) and in the coordinate system for which the best orthotropic representation was found.

Discussion

The methods presented here allow for a complete evaluation of mechanical properties of trabecular bone architecture, using computer reconstructions as the only input. Since (changes in) the mechanical properties of trabecular bone determine (changes in) the mechanical quality of bone, it is expected that in this way an accurate assessment of risk factors related to detrimental changes in architecture, for example due to osteoporosis, is obtained.

A limitation of the methods presented here is that homogenous and isotropic tissue material properties are assumed for the tissue Young's modulus, and thus, the pure mechanical properties of the trabecular *architecture* are found, rather than the mechanical properties of trabecular bone. A value for the tissue modulus must still be based on experiments, in order to obtain realistic values for overall elastic moduli.

With the methods developed here and with recent developments of *in vivo* three-dimensional reconstruction techniques [6,7], it will ultimately be possible to estimate the mechanical properties of the trabecular architecture *in vivo*, which clearly is impossible with traditional mechanical tests. A more immediate purpose is the application to comparative evaluations of *in vitro* trabecular properties.

Acknowledgments This project was sponsored by The Netherlands Foundation for Research (NOW/Medical Sciences), by the National Computing Facilities Foundation (NCF), by the Danish Rheumatism Association (233-588) and by the Danish Research Councils (5210563-1 and 9313411).

References

[1] Fyhrie, D.P., Hamid, M.S., Kuo, R.F. and Lang, S.M. (1992) *Trans. 38th ORS* p. 551

[2] Van Rietbergen, B. Weinans, H., Huiskes, R. and Odgaard, A. (1995) *J.Biomech.* **28**, pp. 69-81.

[3] Odgaard, A., Andersen, K., Ullerup, R., Frich, L.H. and Melsen, F. (1994) *Bone*, **15**, 335-342

[4] Van Rietbergen, B., Weinans, H., Huiskes, R. and Polman, B.J.W (1996) *Int. J. Num. Meth. Eng.* (in press)

[5] Hollister, S.J. and Kikuchi, N. (1992) *Comp. Mech.* **10**, p.73-95

[6] Kinney, J.H., Nichols, M.C. and Lane, N.E. (1994), *Trans. Orthop. Res. Soc.*, **19**, 56

[7] Müller, R., Hildebrand, T. and Rüegsegger, P. (1994), *Phy. Med. Biol.*, **39**, 145-164