The role of trabecular architecture in the anisotropic mechanical properties of bone

Citation for published version (APA):
Rietbergen, van, B., Huiskes, R., Weinans, H., Odgaard, A., & Kabel, J. (1995). The role of trabecular architecture in the anisotropic mechanical properties of bone. In *Bone structure and remodeling* (pp. 137-145). (Recent advances in human biology; Vol. 2). World Scientific.

Document status and date:
Published: 01/01/1995

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

THE ROLE OF TRABECULAR ARCHITECTURE IN THE ANISOTROPIC MECHANICAL PROPERTIES OF BONE

B. VAN RIETBERGEN, R. HUISKES, and H. WEINANS
Biomechanics Section, Institute of Orthopaedics, University of Nijmegen,
P.O. Box 9101, 6500 HB Nijmegen, The Netherlands

and

A. ODGAARD and J. KABEL
Biomechanics Laboratory, Orthopaedic Hospital, University of Aarhus,
Randersvej 1, DK-8200 Aarhus N, Denmark.

ABSTRACT

As yet, no unique relationship between mechanical and structural parameters has been established for trabecular bone. A possible explanation for the variability in the relationships obtained so far is that the results of mechanical tests represent more parameters than those of trabecular morphology alone. In the present study, the results of such a mechanical test are compared to results of a numerical experiment, from which the isolated mechanical role of the trabecular architecture of a bone specimen is obtained. A mechanically tested bone specimen was reconstructed in a computer and converted to a microstructural FE-model. The results of experiment and FE-simulation were, obviously, not identical. It is hypothesized that experimental artifacts are the most important factors affecting the mechanical test results, thus causing variability in the relationships. More accurate relationships are expected when these artifacts can be excluded, for example, by using microstructural FE-models.

1. The Unclear Relationships Between the Mechanical Properties and the Morphology of Trabecular Bone

Because of its load-carrying function the quality of trabecular bone is best characterized by its apparent mechanical properties. The most straight-forward way for the determination of bone quality is in using mechanical testing methods. So far, however, no mechanical tests have been developed that can be used in-vivo. For this reason many investigators have tried to estimate the mechanical properties of bone in an indirect way, from morphological parameters such as apparent density, volume fraction, connectivity or Mean Intercept Length, which can be measured in vivo by using bone imaging and reconstruction techniques. The relationships between morphological parameters and bone stiffness or strength have been investigated in a number of studies for example by using experimental designs in which morphological parameters are correlated with mechanical properties, measured in compression test experiments for a large number of bone samples[1-6]. In spite of these studies, the relationships between morphological parameters and mechanical properties are still unclear. In some studies good correlations were found between stereological measures and (anisotropic) material properties of bone[2,4,7]. In some other studies however, only weak or no correlations were found[8]. When comparing the results of different studies relative to each other, the predictive value of the morphological parameters is even less clear, as different relationships are found.

To explain the variability in the correlation between mechanical properties and bone morphology as described by stereological parameters, three possible causes can be identified: 1) errors in the compression-test results, 2) the morphology of the sample is not very well represented by the parameter that is used, or 3) local variations in the tissue material properties are important for the apparent material properties of trabecular bone.

A number of investigators have addressed experimental errors and have found that boundary effects in the compression test in particular distort the apparent properties (strength, stiffness) obtained (see Keaveny and Hayes[9] and Linde[10] for reviews of this work). This produces an inherent variability in the test results which is significant. There is also an inherent variability in the results of micro-mechanical tests of trabecular specimens, due in particular to size-effects [11,12]. Hence, if the apparent properties are affected significantly by local variations in local trabecular properties, then presently it would be impossible to evaluate them. As a consequence, the only way to purely correlate trabecular architecture and mechanical anisotropy experimentally is to use large numbers of specimens, in order to statistically correct for species, anatomical location and the two factors mentioned above. The numbers required would be virtually prohibitive.

It is, however, possible to investigate the isolated role of trabecular architecture, represented by morphological parameters, in a numerical experiment. In this case, the micro-morphology of the bone is represented in a FE-model, used to simulate compression tests. In this simulation, the apparent elastic constants obtained depend only on trabecular architecture, since all other parameters can be made identical for all tests. In this chapter, this method is introduced and discussed.

2. The True Mechanical Properties of the Trabecular Architecture; the Use of Idealized Models

In a number of studies trabecular architectures have been modeled using idealized analytical or numerical models build of two- or three-dimensional unit cells[13-15]. Although these models can give good insight in the relationships between structural parameters and mechanical properties, they do not represent trabecular architectures very well; two-dimensional models can only represent bone in the case that it has an axi-symmetric architecture, three-dimensional unit cell models can only represent bone which is characterized by a repetitive architecture of structural units.

For a more accurate characterization of trabecular architecture, its three-dimensional features must be modeled in detail. Recently, two different reconstruction techniques have been developed for this. The first technique uses micro-CT scans of a large number of cross sections[16]. With this method a resolution of 50 microns can be obtained. The second method uses a microtome and a digital camera to create images of sequential cross sections[17,18]. With this method a resolution of 1/1000 of the specimen dimension can be obtained, i.e. 10 microns for a 10 mm specimen. With both methods a set of computer images is created, that can be used to reconstruct the three dimensional trabecular geometry in terms of a voxel data set. All voxels in this data set are brick-shaped and have the same size. This data is then used to create microstructural FE-models via a so-called voxel conversion procedure, whereby voxels in the data set are converted to equally sized brick elements in a FE-model.

The conversion of voxel data to FE-models was demonstrated in a number of studies. Fyhrie et al.[19] converted a voxel data set obtained from micro-CT-scanning of a 1.75 mm cubic piece of trabecular bone to a FE-model which they used to determine the tissue stress and strain distribution in the tissue material. Edidin et al.[18] used the serial sectioning technique to model a somewhat larger cubic piece of bone of 2.8 mm and a different voxel conversion technique, whereby the density of voxels were assigned to the Gauss points of larger brick elements. In their study, they found that the apparent modulus estimated from the model was in the range of experimental values. In both of these studies however, the sample size was too small to obtain accurate apparent results for the material properties[20].

At present, two techniques have been developed to model areas of bone that are large enough to obtain valid apparent results. The first technique uses the homogenization theory, whereby the volume is subdivided in smaller sub-volumes[21-23]. The voxel conversion technique is then used to create FE-models of the trabecular architecture in each sub-volume. After solving the FE-problems for the sub-volumes, the apparent mechanical properties of the whole volume can be estimated. The second technique uses large-scale FE-models in combination with special-purpose FE-solving routines[24] to solve the FE-problem for a relatively large piece of bone[25-29]. In earlier studies we have used the latter technique to model a 5x5x3.6 mm specimen taken from the tibial plateau[25,27] and a 10 mm cubic specimen taken from a whale vertebral body[28,29]. For both specimens, the tissue stress and strain distributions as well as the overall mechanical properties were obtained. Experimental results were obtained only for the 10 mm specimen. For this reason, the results of the latter analyses are used in the present study.

3. The Mechanical Properties of a Bone Sample Versus the Mechanical Properties of Its Architecture

In the earlier studies[28,29], the apparent mechanical properties of a 10 mm cubic bone sample were determined using a tri-axial compression test experiment. In this experiment, a prescribed displacement equivalent to 0.3% strain was applied once in the x-, once in the y-, and once in the z-direction. At the bone-platen interface, low-friction conditions were created by using polished steel platens; the other faces of the specimen were left unconstrained in each test. LVDT's were used to measure the transverse strains. The apparent Young's moduli of the specimen in the three directions were calculated from the reaction forces and the specimens cross sectional area. The Poisson's ratios of the specimen were calculated from the ratios between the transverse strain and the longitudinal strain.

The results for the apparent moduli (Table 1), demonstrate that the specimen has anisotropic properties. The anisotropy ratio, which was defined as the ratio of the highest over the lowest modulus, was 1.60. The Poisson's ratio's calculated from the transversal strains for this sample range from 0.11 to 0.35, with the highest values in the transverse z-direction.

To determine the mechanical properties of the architecture of the bone specimen, a detailed microstructural FE-model of the same specimen was created. For this purpose, the specimen was sectioned in 20 microns thick sections, using a microtome[17]. Each section was digitized using a high resolution video camera. The magnification factor was chosen such that the (square) pixels in the resulting images were also 20 micron in size.

The bone voxels in the resulting voxel data set were then converted to elements in the FE-model, using a pre-processing code developed in our Lab. The pre-processing consists of four stages. In the first stage, the area fraction of each section in the data set is calculated. Sections (at the periphery) with an area fraction less than 75% of the bone volume fraction were removed from the data set to ensure that boundary artifacts due to cutting of the specimen are not represented in the FE-mesh. For the bone specimen investigated, 0.38 mm was removed in the x-direction, 0.23 mm in the y-direction and 0.12 mm in the z-direction. In the second stage of pre-processing, the number of voxels in the data set was reduced by grouping 4x4x4 voxels in a courser grid with 80 micron voxels. A new voxel is considered to represent bone if more than half of its original voxels represents bone. In the third stage of pre-processing, voxels that are not connected to the main structure are removed from the data set to avoid singularities when solving the FE-problem. In the final stage, the resulting bone voxels were converted to elements in the FE-model, resulting in a FE-mesh with 540,217 elements and 956,686 nodal points (Fig. 1). From this reconstruction, it can be seen that the specimen has a somewhat tube-like architecture, oriented diagonal in the x-y plane.

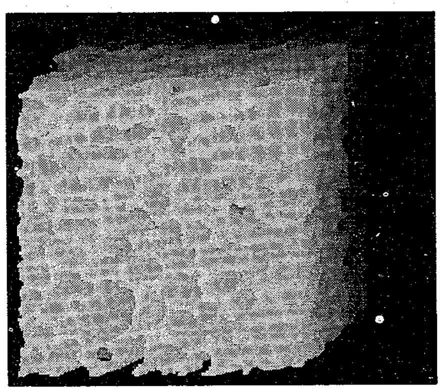

Fig. 1 The FE-model of the trabecular bone sample

The boundary conditions for the FE-model were chosen such as to represent the situation during the compression-test experiments. Only the displacements in the longitudinal direction were constrained at the bottom face of the specimen, and prescribed at the top face. All other faces were left unconstrained, representing an idealized compression-test experiment with no friction between platens and bone. By aligning the longitudinal axis once with the x-, once with the y- and once with the z-axis, the compression test experiments in each direction were simulated, and the apparent moduli and transverse strains were calculated.

For the initial calculations, all elements in the FE-model were assigned linear elastic isotropic material parameters with an arbitrarily chosen Young's modulus of 1 GPa and a Poisson's ratio of 0.3. The apparent moduli found in the FE-model for this tissue modulus are also listed in Table 1. For this model an anisotropy ratio of 1.35 was calculated. In each direction, a tissue Young's modulus $E^t_{\exp}$ was calculated, such that the experimentally determined Young's modulus $E^a_{\exp}$ and the apparent modulus determined in the FE-model E^a_{sim} are exactly the same in that direction, using the following relation:

$$E^t_{\exp} = \frac{E^a_{\exp}}{E^a_{sim}} E^t_{sim} \quad (1)$$

with E^t_{sim} the initial Young's modulus of 1 Gpa. The average value of the three tissue moduli thus obtained was 5.33 GPa, and this value was taken as the trabecular tissue modulus for this specimen. The apparent moduli found in the simulation after scaling the results to this tissue modulus, are shown in Fig. 2 in comparison to the experimental values.

Unlike the Young's moduli, the transverse strains found in the simulation are independent of the tissue modulus chosen, as displacements were prescribed at the apparent level. The Poisson's ratios calculated from the transverse strains in the FE-model are shown in Fig. 3, in comparison to the experimental values. From this figure it can be seen that the Poisson's ratios calculated in the simulation, which range from 0.15 to 0.38, with the highest values in the transversal z-direction, show the same trend, but overestimate the ratios measured in the experiment.

	Experiment apparent moduli	FE-model apparent moduli (for E^t_{sim}= 1GPa)	Tissue moduli calculated from eq. (1)
	E^a_{exp} MPa (SD)	E^a_{sim} MPa	E^t_{exp} GPa
x	593 (17.1)	107.85	5.50
y	605 (18.6)	104.87	5.77
z	377 (11.0)	80.01	4.71

Table 1

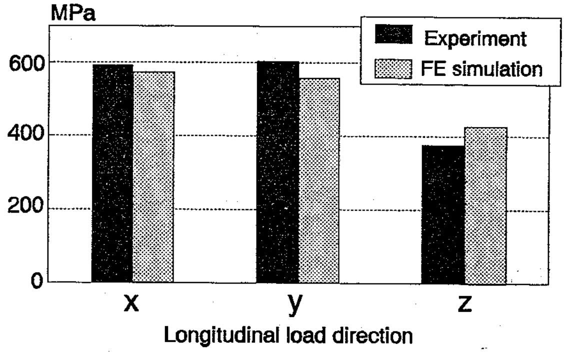

Fig. 2 Apparent Young's moduli measured in the experiment and in the FE-simulation after scaling the results for a tissue Young's modulus of 5.33 GPa

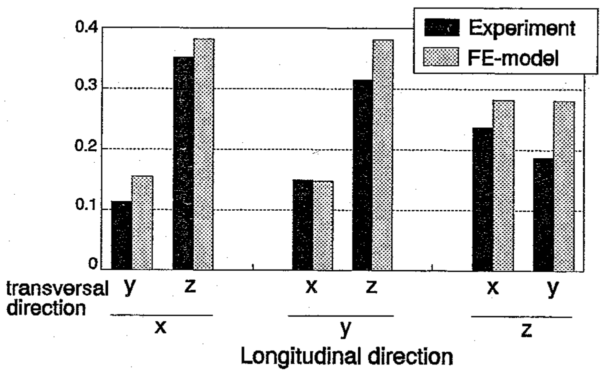

Fig. 3 Poisson's ratios measured in the experiment and in the FE-simulation

4. Assessment of the Role of the Trabecular Architecture in the Experiment; the Effect of Experimental Artifacts

The anisotropic properties found in the experiment are reasonably well reproduced by the FE-model. As the anisotropy in the FE-model is due to its architecture only, this indicates that trabecular architecture is the main determinant for the anisotropy of trabecular bone.

Differences between the results of the experiment and those of the FE-

simulations can be explained by inaccuracies in the compression test experiment, one of the major suspects being the boundary artifacts due to cutting. A number of studies have described these artifacts and their possible consequences for the apparent mechanical properties measured in experiments[30-33]. In the FE-model, these damaged areas were removed from the model to allow for a meaningful FE-calculation. It is possible that these boundary areas, that are present in the experiment but not in the FE-simulation, will result in a non-uniform strain distribution in the bone experiment[30,31,33], with strains larger than the prescribed 0.3% in the damaged areas and smaller strains in the bulk area. As the transversal strains measured in the experiments are related to the bulk strain, the existence of damaged boundary areas can explain why the transversal strains measured in the experiment are less than those measured in the FE-simulation. The non-uniform strain distribution will also results in an underestimation of the Young's modulus in the experiment[33], which, according to eq. 1, will also result in an underestimation of the tissue modulus. For this reason, the tissue modulus found in the present study is to be considered as a lower bound.
Furthermore, it is possible that these end-effects have a more severe influence in the directions with lower stiffness, since it is likely that the thinner trabeculae oriented in the directions with the lower moduli are more damaged than the thicker trabeculae oriented in the direction with the higher Young's moduli. The fact that the underestimation of the Poisson's ratios is more severe when the specimen is loaded in the direction with the lowest modulus (the z-direction) supports this hypothesis. This anisotropic end-effect can explain why the anisotropy ratio found in the experiment is larger than found for the FE-model.

Another experimental artifact that can affect the comparability of experimental and simulation results is the existence of friction between bone and platens in the experiment, which is not simulated in the FE-model. It has been shown that friction can also result in an overestimation of the anisotropy[28].

5. The Application of Microstructural FE-models for a Pure Correlation Between Architectural Parameters and Mechanical Properties

It is hypothesized that the experimental artifacts in the compression test-experiment are the largest source of errors in the determination of the relationships between structural parameters and mechanical properties of trabecular architecture. The application of microstructural FE-models to simulate the compression test can be used to reduce these errors because in these simulations the experimental artifacts are excluded. The voxel data sets that are used to create the FE-mesh can also be used to determine morphological parameters of the same bone samples. When a large number of reconstructed bone samples is available, it can be investigated which (combination of) morphological parameters best describes the mechanical properties of the trabecular structure.

With the development of in-vivo scanning and reconstruction techniques, the microstructural FE-models can also offer a unique way to measure the mechanical properties of trabecular bone in-vivo. In the future it may be possible to directly calculate the mechanical properties of each reconstructed piece of trabecular bone, thus bypassing the intermediate step of stereological parameters for the determination of the mechanical properties.

6. Acknowledgements

This work was sponsored by The Netherlands Foundation for Research (NWO/Medical Sciences), by the National Computing Facilities Foundation (NCF), and by the Danish Rheumatism Association (233-588).

7. References

1. Carter D.R. and Hayes W.C., "The compressive behavior of bone as a two-phase structure", *J. Bone Jt. Surg.* **59**, 954-962 (1977).
2. Goulet R.W., Ciarelli M.J., Goldstein S.A., Kuhn J.L., Feldkamp L.A., Kruger D., Viviano D. and Champlain F., "The effects of architecture and morphology on the mechanical properties of trabecular bone", *Trans. 34th ORS* **13**, 73 (1988).
3. Hodgskinson R. and Currey J.D., "Young's modulus, density and material properties in cancellous bone over a large density range", *J. of Mat. Science: Materials in Medicine* **3**, 377-381 (1992).
4. Turner C.H., Cowin S.C., Rho J.Y., Ashman R.B. and Rice J.C., "The fabric dependence of the orthotropic elastic constants of cancellous bone", *J. Biomech.* **23**, 549-561 (1990).
5. Rice J.C., "On the dependence of the elasticity and strength of cancellous bone on apparent density", *J. Biomech.* **21**, 155-168 (1988).
6. Ciarelli M.J., "Evaluation of orthogonal mechanical properties and density of human trabecular bone from the major metaphyseal regions with materials testing and computed tomography", *J. Orthop. Res.* **9**, 674-682 (1991).
7. Hodgskinson R. and Currey J.D., "The effect of variation in structure on the Young's modulus of cancellous bone: a comparison of human and non-human material", *J. Eng. Med.* **204**, 115-121 (1990).
8. McCubbrey D.A., Cody D.D., Gross G.J., Goulet R.W., Peterson E. and Goldstein S.A., "Relationships between regional material properties, density, and architecture of the human proximal femur", *ASME/BED* **22**, 131-133 (1992).
9. Keaveny T.M. and Hayes W.C., "A 20 years perspective on the mechanical properties of trabecular bone", *J. Biomech. Eng.* **115**, 534-542 (1993).
10. Linde F., Elastic and viscoelastic properties of trabecular bone by a compression testing approach. Kobenhavn, Laegeforeningens Forlag, (1993).
11. Choi K., Kuhn J.L., Ciarelli M.J. and Goldstein S.A., "The elastic moduli of human subchondral trabecular, and cortical bone tissue and the size dependency of cortical bone modulus", *J. Biomech.* **23**, 1103-1113 (1990).
12. Rho J.Y., Ashman R.B. and Turner C.H., "Young's modulus of trabecular and cortical bone material: ultrasonic and microtensile measurements", *J. Biomech.* **26**, 111-119 (1993).
13. Gibson L.J., "The mechanical behavior of cancellous bone", *J. Biomech.* **18**, 317-328 (1985).
14. Beaupre G.S. and Hayes W.C., "Finite element analysis of a three-dimensional open-celled model for trabecular bone", *J. Biomech. Eng.* **107**, 249-256 (1985).
15. Hollister S.J., Fyhrie D.P., Jepsen K.J. and Goldstein S.A., "Application of homogenization theory to the study of trabecular bone mechanics", *J. Biomech.* **24**, 825-839 (1991).
16. Feldkamp L.A., Goldstein S.A., Parfitt A.M., Jesion G. and Kleerekoper M., "The direct examination of three dimensional bone architecture in vitro by computed tomography", *J. Bone Min. Res.* **4**, 3-11 (1989).

17. Odgaard A., Andersen K., Melsen F. and Gundersen H.J.G., "A direct method for fast three-dimensional serial reconstruction", *J. Microscopy* **159**, 335-342 (1990).
18. Edidin A.A., Dawson J.M., Zhu M. and Chinchalkar S., Direct estimation of the modulus of cancellous bone using a variable-stiffness FE model; in Transactions of the 39th Annual meeting of the Orthopaedic Research Society. Chicago, IL, ORS, pp 589. (1993),
19. Fyhrie D.P., Hamid M.S., Kuo R.F. and Lang S.M., "Direct three-dimensional finite element analysis of human vertebral cancellous bone", *Trans. 38th ORS* 551 (1992).
20. Harrigan T.P., Jasty M., Mann R.W. and Harris W.H., "Limitations of the continuum assumption in cancellous bone", *J. Biomech.* **21**, 269-275 (1988).
21. Hollister S.J. and Kikuchi N., "Direct analysis of trabecular bone stiffness and tissue level mechanics using an element-by-element homogenization method", *Trans. 38th ORS* 559 (1992).
22. Hollister S.J., Brennan J.M. and Kikuchi N., Recent advantages in computer methods in biomechanics & biomedical Engineering. Swansea, UK, Books & Journals Int. LTD, (1992).
23. Hollister S.J., Brennan J.M. and Kikuchi N., "A homogenization sampling procedure for calculating trabecular bone effective stiffness and tissue level stress", *J. Biomech.* **26**, (1993).
24. Van Rietbergen B., Weinans H., Polman B.J.W. and Huiskes R., "A fast solving method for large-scale FE-models generated from computer images, based on a Row-By-Row matrix-vector multiplication scheme", *ASME/CED* **6**, 47-52 (1994).
25. Van Rietbergen B., Weinans H., Huiskes R. and Odgaard A., Three dimensional analysis of a realistic trabecular bone structure, using a large-scale FE-model; in Langrana N.A., Friedman M.H., Grood E.S. (eds): BED Bioengineering Conference. New York, ASME, pp 250-253. (1993),
26. Hollister S.J. and Kikuchi N., "Comparison of trabecular tissue strains computed by homogenization theory to direct Finite Element calculations", *ASME/BED* **24**, 258-261 (1993).
27. Van Rietbergen B., Weinans H., Huiskes R. and Odgaard A., "A new method to determine trabecular bone elastic properties and loading using micromechanical Finite-Element models", *J. Biomech.* **28**, 69-81 (1995).
28. Van Rietbergen B., Weinans H., Huiskes R., Odgaard A. and Kabel J., "Determination of tissue loading in a trabecular bone specimen, using a full scale FE-model", *Trans. 40th ORS* 58 (1994).
29. Van Rietbergen B., Huiskes R., Weinans H., Odgaard A. and Kabel J., "Determination of trabecular bone tissue and apparent properties, using a full scale FE-model and experimental results", *Transactions of EORS* **4**, 84 (1994).
30. Keaveny T.M., Borchers R.E., Gibson L.J. and Hayes W.C., "Theoretical analysis of the experimental artifact in trabecular bone compressive modulus", *J. Biomech.* **26**, 599-607 (1993).
31. Zhu M., Keller T.S. and Spengler d.m., "Effects of specimen load-bearing and free surface layers on the compressive mechanical properties of cellular materials", *J. Biomech.* **27**, 57-66 (1994).
32. Linde F. and Hvid I., "The effect of constraint on the mechanical behaviour of trabecular bone specimens", *J. Biomech.* **22**, 485-490 (1989).
33. Odgaard A. and Linde F., "The underestimation of Young's modulus in compressive testing of cancellous bone specimens", *J. Biomech.* **24**, 691-698 (1991).