Morphology and mechanical properties of the cancellous bone in the mandibular condyle
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Abstract
The structure of the cancellous bone in the human mandibular condyle is characterized by plate-like trabeculae oriented in the sagittal plane. We tested the hypothesis whether this structure reflects the mechanical loading of the condyle. For this purpose a finite element model of the condyle was developed to analyze the occurring strains during static compressive loading. The principal strains in the trabecular bone were primarily oriented in the sagittal plane. The first component was compressive and oriented superoinferiorly, the second component was negligibly small and oriented mediolaterally, the third component was tensile and oriented anteroposteriorly. The tensile strain was almost equal to the compressive strain. This relatively large tensile strain was due to the anteroposterior bulging of the cortex, which caused a tensile stress in the cancellous bone. It suggests that the cancellous bone also has to resist significant tensile forces. The orientation of the principal strains within the sagittal plane changed with the direction of the applied load. It was concluded that the plate-like trabecular structure of the mandibular condyle is optimal to resist compressive and tensile strains.
Introduction

According to the law of bone remodeling (Wolff, 1892) the trabecular structure of bone is optimized to offer maximum resistance to stresses and strains with a minimum amount of bone mass. By using finite element models, the correspondence between trabecular structure, bone density, and mechanical loading has been demonstrated in several studies (e.g., Smit et al., 1997; Mullender et al., 1998; Huiskes et al., 2000).

Recently, the three-dimensional structure of the cancellous bone of the human mandibular condyle was analyzed by Giesen and Van Eijden (2000). They found that the cancellous bone mainly consists of parallel plates perpendicular to the mediolateral condylar axis. This means that the trabecular structure can withstand larger stresses in sagittal planes than in the mediolateral direction, as indeed has been demonstrated by mechanical tests (Giesen et al., 2001). This suggests that the orientation of the plate-like structure is related to the orientation of the stresses, i.e., that the condyle is optimally adapted to sustain stresses and strains occurring in vivo. Until now, however, a detailed analysis of the stresses and/or strains in the human mandibular condyle has never been performed. The available finite element models (e.g., Korieth et al., 1992; Beck et al., 2000) do not provide enough details to study the distribution of strains in the bone of the condyle.

In the present study, we determined the strains occurring in the mandibular condyle due to static loads to verify if the structure of the cancellous bone is optimized to sustain these loads. For this purpose, we developed a three-dimensional finite element model of the mandibular condyle. The strain matrix, the principal strains, and the total principal strain in the condyle were calculated for three different load cases. Furthermore, the deformation of the condyle due to the loading was analyzed.

Material and Methods

Finite Element Model

The right condyle of a dried mandible was separated from the rest at the collum by an electrical saw. The condyle was scanned with a micro-CT scanner (μCT 20, Scanco Medical AG, Zürich, Switzerland). The scan had a pixel size of 34 x 34 μm² and the interslice distance was 34 μm. Bone tissue was identified from background noise with a uniform threshold (Giesen and Van Eijden, 2000). Using a bitmap editor the trabecular structure was removed from all CT slices and artifacts in the
cortex were repaired. Next, all the cortical surface points (pixels) were extracted. A point belonged to the surface if it contained bone and at least one of the six neighboring points was empty. The surface points were divided into three sets: the outer surface, the inner surface and the saw plane. After filtering, both the inner and outer surface sets contained approximately 400,000 points.

Through the points of the saw plane a plane was fitted. To model the inner and outer cortical surfaces, 30,000 points were selected randomly from both surfaces. A method developed by Hoppe (1994) and Schweitzer (1996) was used to fit surfaces through these data points.

In order to make a volume mesh, a closed surface mesh had to be made first. Triangular meshes were generated from the subdivision models of the inner and the outer surface of the cortex. The boundary vertices of these meshes were projected rectilinearly on the saw plane. The meshes and the projections of the vertices were imported in an automated mesher (Mentat 3.2, MSC Software). First, the spaces between the projected boundaries and the surface boundaries were closed with a triangular mesh. Next, the area within the projection of the inner boundary as well as the area between the projected boundaries was closed with planar triangular meshes. Finally, tetrahedron meshes were created for the cancellous and the cortical bone volumes (44,000 and 13,000 tetrahedrons, respectively). In Fig. 1 a frontal view of the condyle obtained from the unedited CT scan and two views of the model of the cortical surface are shown. The model matched the CT scan very well, as the mean distance between the outer surface points and the surface model was 14 μm. The triangular mesh of the outer surface contained only 5,632 vertices.

The cancellous and cortical bone volumes were modeled as an isotropic homogeneous material. For cortical bone an elastic (E-) modulus of 19.0 GPa (Rho et al., 1993) was used. Based on a mean condylar cancellous bone volume fraction of 17% (Giesen and Van Eijden, 2000), the estimated E-modulus for cancellous bone was 1.11 GPa (Rho et al., 1993). Poisson ratios of 0.32 and 0.20 (Carter and Hayes, 1977; Kabel et al., 1999) were used for the cortical and the cancellous bone, respectively.

Simulations
To mark the boundary of the articular surface on the finite element model, the articular surface and its rim were measured with an electromagnetic tracking device (Space Tracker, Polhemus 3Space). A three-dimensional polynomial function was fitted through the surface points (Van Ruijven et al., 1999,2000). This polynomial
function was fit to the outer surface of the finite element model, after which the points of the articular rim were projected on the outer surface of the model (Fig. 1).

The articular area was equally divided into anterior, apical and posterior parts, which were loaded separately with a constant pressure. Since the parts had a surface

Fig. 1 The original CT-scan (A) and the finite element model (B+C). The thick line marks the border of the articular area.
area of $7 \times 10^5$ m$^2$, and the total estimated load during static clenching is approximately 300 N (Koolstra et al., 1988), a pressure of 4.28 MPa was used. The nodes belonging to the saw plane were fixed.

The finite element problem was solved with MARC (MSC Software) on a Beowulf Linux-PC cluster. Principal strains as well as the total principal strain were calculated for every cancellous and cortical bone element. The total principal strain of an element is equal to the change in volume of that element. Three-dimensional plots were made with The Visualization Toolkit v3.1 (Kitware) on a Windows/Intel computer.

**Results**

For each of the load cases, the deformation of the condyle in the midsagittal cross-section is shown in Fig. 2. In all simulations the condyle was compressed along the mean loading direction and extended perpendicular to this direction. The amount of compression and extension were estimated to be approximately 0.2%. Frontal cross-sections did not reveal a deformation in the mediolateral direction. For all load cases together, 95% of the elements of the cortical bone had a strain less than 1,600

![Deformation of the midsagittal cross-section of the condyle due to the three loads.](image)

**Fig. 2** Deformations of the midsagittal cross-section of the condyle due to the three loads. The gray area indicates the unloaded shape. The lines depict the deformed shapes. For reasons of clarity, these deformations were amplified fifty times. At the bottom the deformation was zero, because the saw plane was fixed during the simulation. The thick lines mark the region where the loads were applied.
μstrain, and 95% of the elements of the cancellous bone had a strain less than 4,600 μstrain.

The mean magnitudes of the three principal strains in the cancellous bone elements are given in Table 1. The first principal strain was always compressive. The third principal strain was always tensile and only 10-20% smaller in absolute value than the first. The second principal strain alternated between compressive and tensile. Its mean magnitude as well as its standard deviation, however, was negligible small compared to the other principal strains.

The total principal strains and the magnitudes and directions of the first and third principal strain at different positions in the condyle are shown in Fig. 3. The total principal strain was dependent on the load case. It was minimal at the apical load case, and maximal at the posterior load case. Furthermore, the total principal strain changed across the condyle. In every cross-section the largest total principal strains were found cranially in the region just below the loaded area. Mediolateral differences were relatively small.

Within the cancellous bone, the directions of the first and third principal strains coincided with the sagittal planes. Compression occurred in the supero-inferior direction (direction of the load), extension occurred in the anteroposterior direction (rectangular to the direction of the load). The orientation and magnitudes of the principal strains in the sagittal plane depended on the load case. The angle between the anterior and the posterior load was 80°. The apical load case resulted in the smallest principal strains. Within one load case, the orientation was approximately constant throughout the condyle. The magnitudes of the principal strains varied throughout the condyle. They were maximal in the cranial region just below the area where the load was applied. In the mediolateral direction the differences were small.
Fig. 3 Total principal strain and the principal strains for the three different load cases. The total principal strain is indicated with colors. The color bar gives the total principal strain in μstrain. The orientations and magnitudes of the principal strains in the sagittal plain are indicated with the black lines. The strains of only a random selection of the elements are shown.
Chapter 3

Discussion

Often the principal orientations and density of the cancellous bone are compared with stress related parameters (stress trajectories: Wolff, 1892; principal stresses: Carter et al., 1989; strain energy density: Huiskes et al., 1987; Weinans et al., 1992). In recent studies, strains or strain derived parameters have become more popular (energy equivalent strain: Mikić and Carter, 1995; strain gradients: Turner et al., 1997; strain rate: Mosley and Lanyon, 1998; equivalent strain: Smit and Burger, 2000). This is more in agreement with studies, showing that bone cells are sensitive for (pulsating) fluid streams (Klein-Nulend et al., 1995; Bakker et al., 2001) in the lacunae and canaliculi. These are caused by strain gradients and strain rates (Judexx et al., 1997). In the present study, strains were analyzed, because strain gradients as well as strain rates are proportional to the strain.

A number of assumptions had to be made for the simulations. Since the bone volume fraction was known, we assumed that the volume fraction was equal to the bone density and used the E-moduli found by Rho et al. (1993) for cortical and cancellous bone. The cancellous bone was modeled isotropic, because only then a possible correspondence between the orientation of the trabeculae and the principal strains can be expected. Experimentally determined E-moduli on specimens from the cancellous bone of the condyle (Giesen et al., 2001) were half the value used in this study. For a reliable calculation of the force distributions, however, the ratio of the moduli for cortical and cancellous bone is more important than the absolute value. Rho et al. (1993) used the same protocol for determining the moduli for both types of bone. Literature values of the Poisson ratios of other cortical and cancellous bones have been used. We do not expect, however, that the results of the present study are very sensitive to the value of the Poisson ratio, because the volume changes are small compared to the strains. Finally, there is no experimental data available, which describes the contact area and the distribution of the contact forces during static clenching. In the present study, the strain distributions in the mandibular discus calculated by Beek et al. (2000) were used to model the shape of the loaded areas.

Despite these limitations, the magnitudes of the principal strains found in the present study are in agreement with experimentally determined strains. During in vivo measurements strains of up to 2000 μstrain have been found in cortical bone of the mandible (Hylander and Johnson, 1992, 1997). In vivo measurements of cancellous bone strains are not available, but in vitro experiments show that cancellous bone can be subjected up to 5000 μstrain without being damaged (Keaveny et al., 1994; Wachtel and Keaveny, 1997).
In the cancellous bone of the condyle, the tensile strain in the anteroposterior direction was almost as large as the compressive strain in the superoinferior direction. The Poisson ratio used in the simulations is too small to explain the tensile strain as a result of the compression. This means that, besides the superoinferiorly-oriented compressive stress, there was also an anteroposteriorly-oriented tensile stress acting on the cancellous bone. Most likely, the anteroposterior bulging of the cortex caused the tensile stress. This also implies that the bulging was not caused by the cancellous bone, but by other factors (e.g., shape of the cortex, shape of the loaded area, etc.). Apparently, the cancellous bone not only serves to resist compression in the superoinferior direction, but also to resist tension in the anteroposterior direction. It should be noted that the fixation of the saw plane prevents any anteroposterior extension near the saw plane. It is therefore possible that in reality even larger tensile strains occur.

In the mediolateral direction the strains were negligible. This is probably related to the fact that the compressive and tensile strains in the sagittal plane were almost equal. Compressive strains in the sagittal plane cause extension in the mediolateral direction, while tensile strains will result in compression in the mediolateral direction. Since the compressive and tensile strains were almost equal in the simulations, it could be expected that the mediolateral strain would be negligible.

The mean principal strain was smallest for the apical load case. The percentile variation of the mean principal strain was also smallest for the apical load case. This implies that the apical load is distributed more evenly throughout the condyle than the other loads. Probably, not only the mean strain is lower for apical loads, but also the ratio maximal strain/mean strain. Therefore, the present results suggest that the condyle is more optimized to sustain apical loads than anterior and posterior loads.

The strains in the cancellous bone were concentrated in sagittal planes, both tensile and compressive. The orientation of these strains rotated over an angle of 80° in this plane by varying the load case. To withstand these strains, a plate-like structure with the plates parallel to the sagittal plane is the optimal structure. Note that such a plate-like structure not only withstands compression in sagittal planes, but also tension. This is exactly the structure Giesen and Van Eijden (2000) found in the human mandibular condyle. They also found that the bone volume fraction and the trabecular thickness are higher in the superior region of the condyle. This also corresponds with the regions where the highest total principal strains were found. Therefore, the results of the present study suggest that the law of bone remodeling is also applicable to the trabecular structure of the mandibular condyle.
Chapter 3

References


