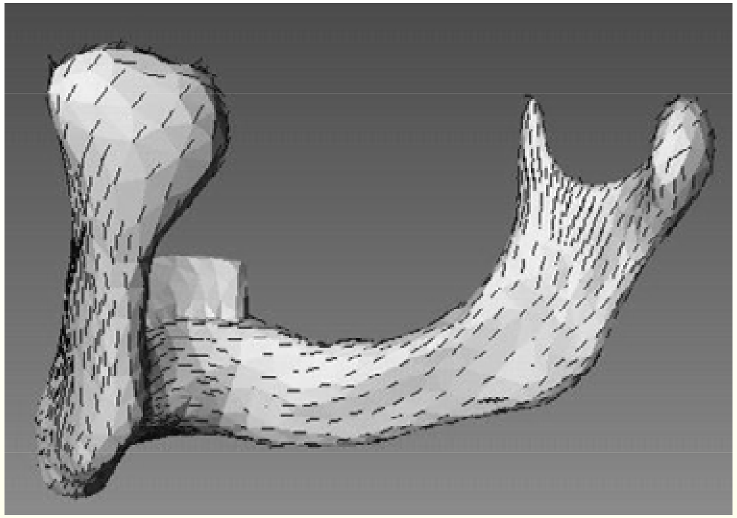


Anisotropy of Human Bone demonstrated for the Human Mandible

C. Kober (a), C. Hellmich (b), S. Stübinger (c),
R. Sader (d), H.-F. Zeilhofer (e)

(a) HAW Hamburg, (b) Vienna Univ. of Technology,
(c) Univ. Zurich, (d) Univ. of Frankfurt, (e) Univ.-Hospital Basel

Germany – Austria – Switzerland

Overview

A) Introduction

B) Methods

- B.1) Theoretical and experimental background
- B.2) Reconstruction of the anisotropic trajectories
- B.3) Realization for the simulation
- B.4) Chain of software tools and requirements

C) Results

D) Conclusion

E) Discussion and Outlook

Software:

- Amira 4.1.2, Amira 5.2.2, www.amiravis.com
- Kaskade 3.1,ZIB Berlin, adaptive finite Element code

Case:

partially edentulous mandible of the female Visible Human data set (CT)

A) Introduction

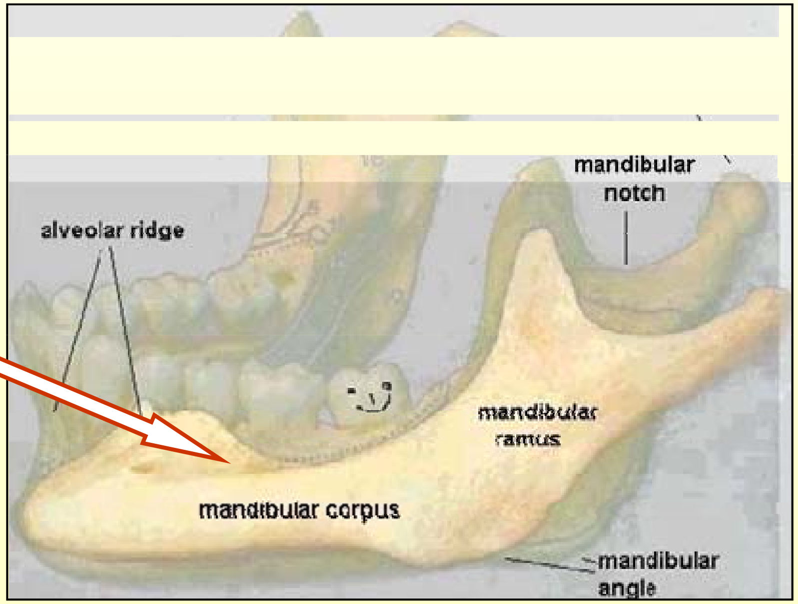
imws
TU VIENNA
HFZ
UNIVERSITÄT FRANKFURT AM MAIN
Kantonsspital Basel Universitätskliniken
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

General purpose of structural mechanics simulation in engineering:

- **prediction of deformation, stress, and strain profiles**
- **prevention of structural failure**
- **...**

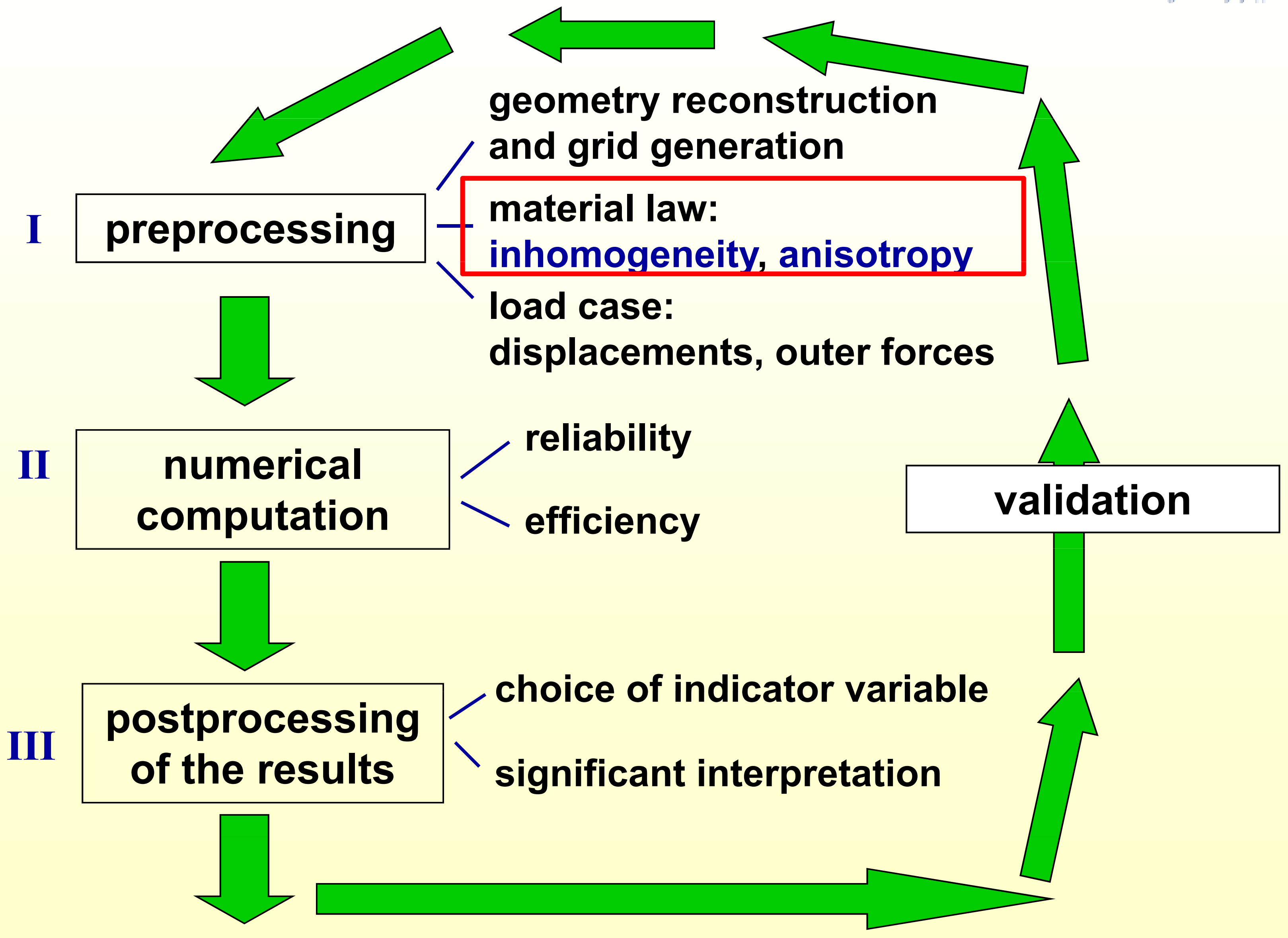
Additional motivation of structural mechanics simulation in biomechanics:

- **adaptation of the consistency of bone due to genetic, biological, and mechanical influence factors**
- **severe changes of human bony organs during life time**

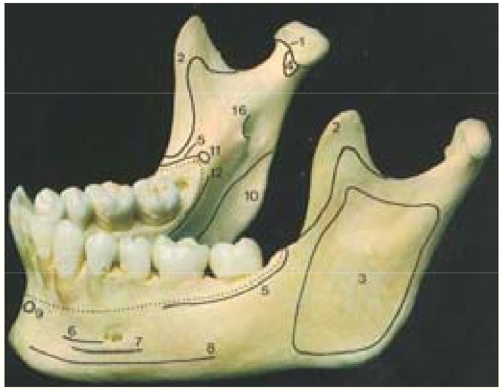


General setup of an FEM-project:

Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences



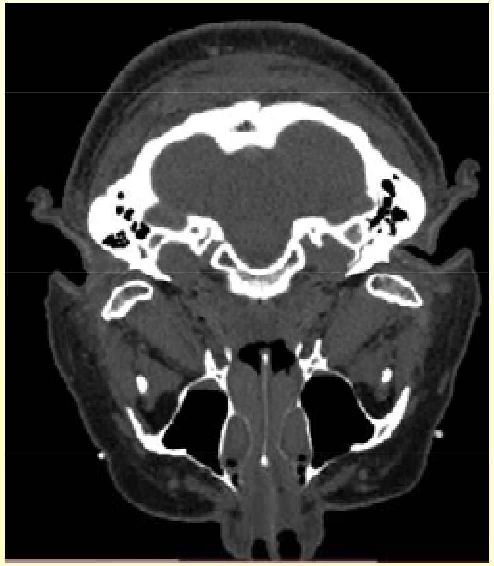
Appropriate formulation of the **material law**



a) Strain < 0.3 %: approximately linear elastic behavior of bone

b) Generalized Hooke's law:

$$\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl}$$



Tissue inhomogeneity

in some sense 'directly' accessible via the gray values of the CT-data

Tissue anisotropy

not accessible via CT-data, alternative concept needed

B) Methods

B.1) Theoretical and experimental background

COLLAGEN MOLECULES

a certain morphology in the bone ultrastructure (Hellmich a. Ulm, 2003)

bone tissues' anisotropy (Lees et al., 1979, Hellmich a. Ulm, 2002).

<u>Therefore</u>

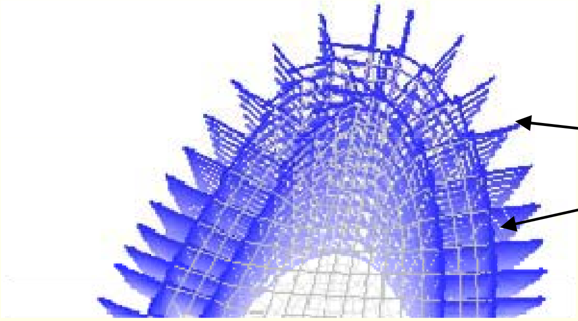
Estimation of the trajectories based on

- the organ's macroscopic morphology, namely its geometry
- the organ's inner material distribution
- the distribution of the CT or Hounsfield values

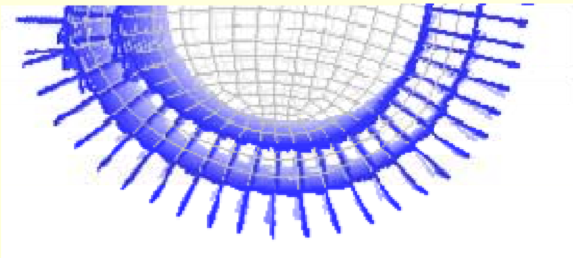
Experimental background:

by experimental evidence:

assumption of orthotropic symmetry



radial,
circumferential,
and axial trajectories
of orthotropic elasticity

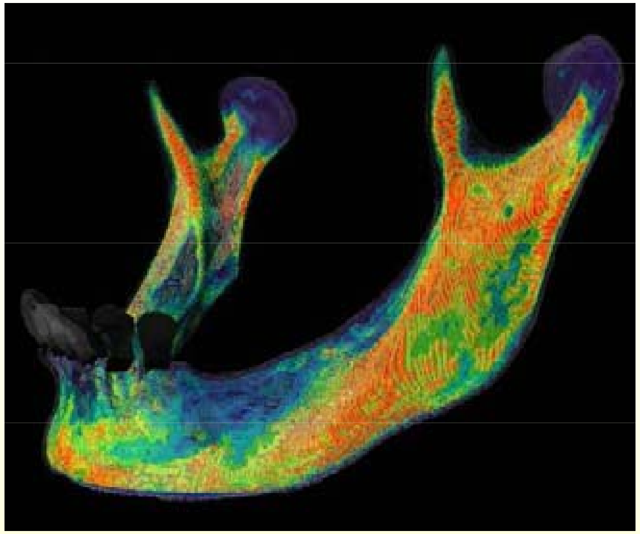


constant elastic coeff. for cortical human jaw bone according to Ashman et al. (1987)

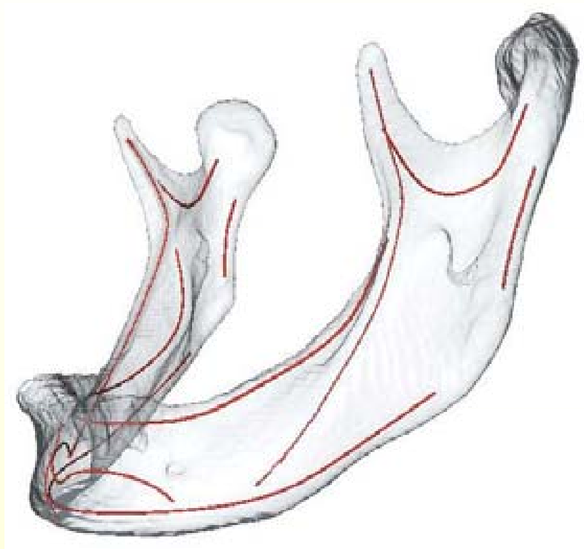
E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
10.8 GPa	13.3 GPa	19.4 GPa	0.309	0.381	0.249	3.81 GPa	4.12 GPa	4.63 GPa
The 1-direction is radial, the 2-direction is circumferential, and the 3-direction is axial.								

Estimated elastic coefficients for spongy bone: tenth part of the one of cortical bone

By means of biomedical visualization:



volumetric profile* of
the distribution of the CT
or Hounsfield values

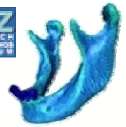


reconstruction of
the inner skeleton

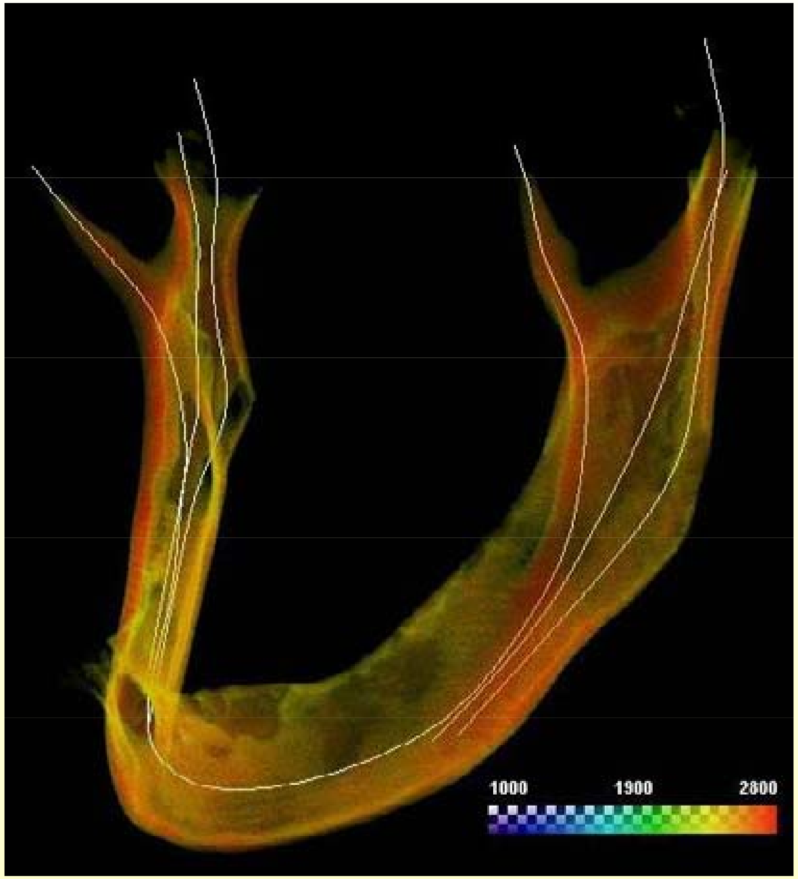
Justified by the micromechanic theory, the inner skeleton provides us with "guiding lines" for the anisotropic trajectories.

*Kober, Sader, Zeilhofer ,cars2003

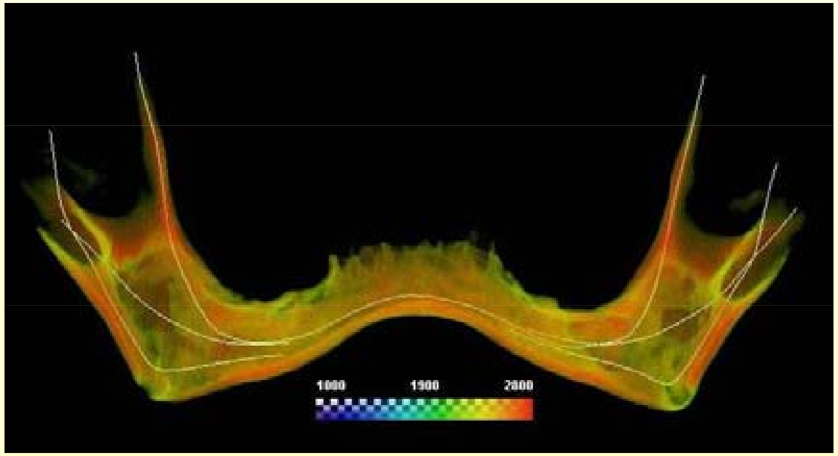
B.2 Four-step procedure for the reconstruction of the anisotropic trajectories :



Step 1: derivation of an individual inner skeleton of the mandible



based on
- *the patient's individual anatomy*
- *the volumetric profile of the (optical) tissue density*



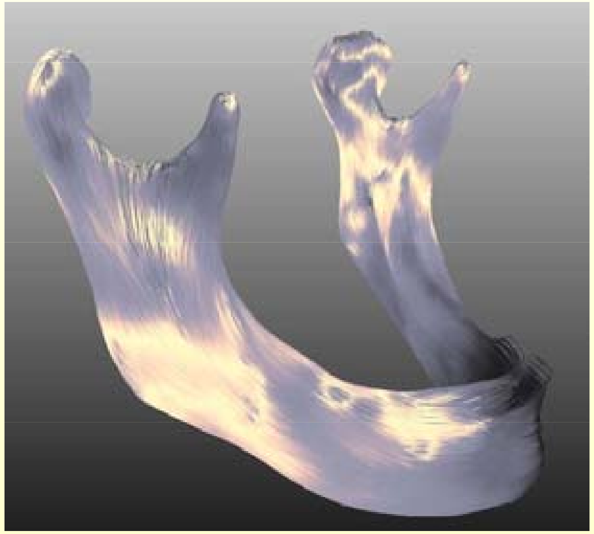
Simplifications at the teeth and at the incisura

Step 2: extension of the skeleton to a (nearly) continuous three dimensional vector field,
problem. bifurcation regions at the mandibular rami

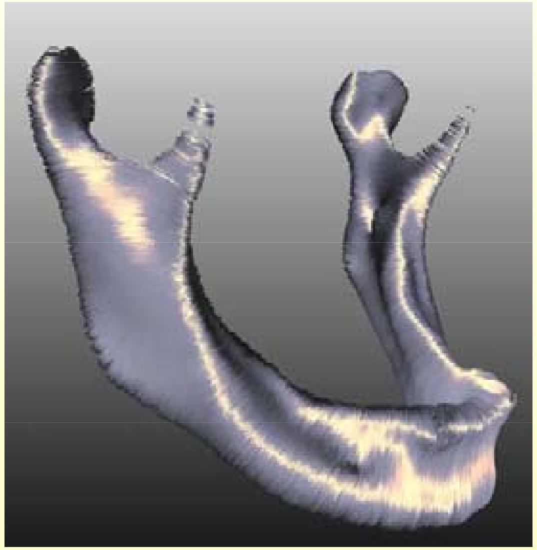
Step 3: construction of the radial trajectories
construction aligned to the surface of the mandible

Step 4: construction of the circumferential and the axial trajectories

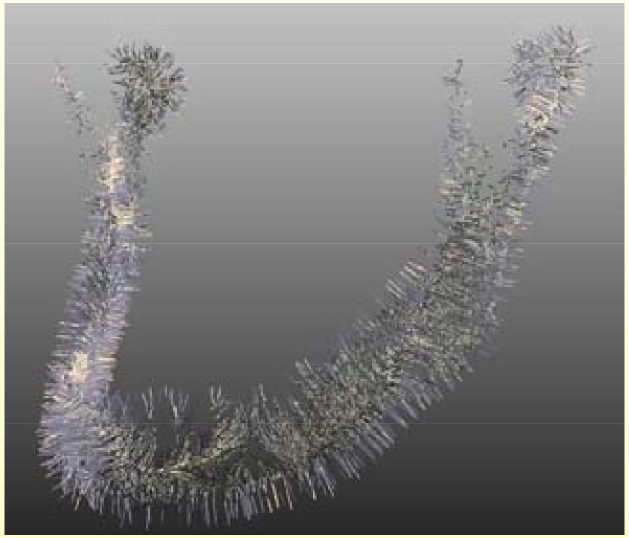
Results:



axial



circumferential



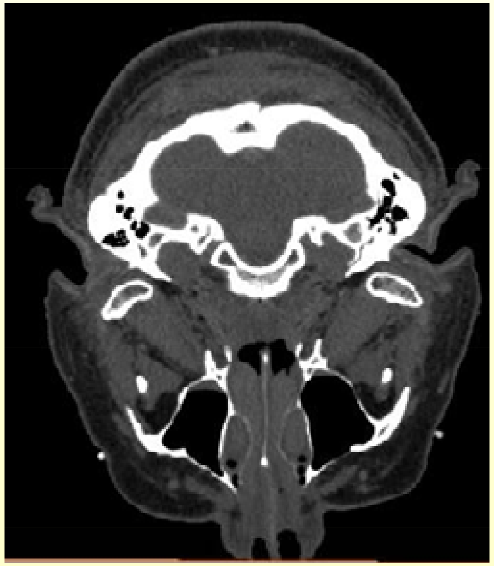
radial

Axial, circumferential, and radial trajectories of orthotropic elasticity

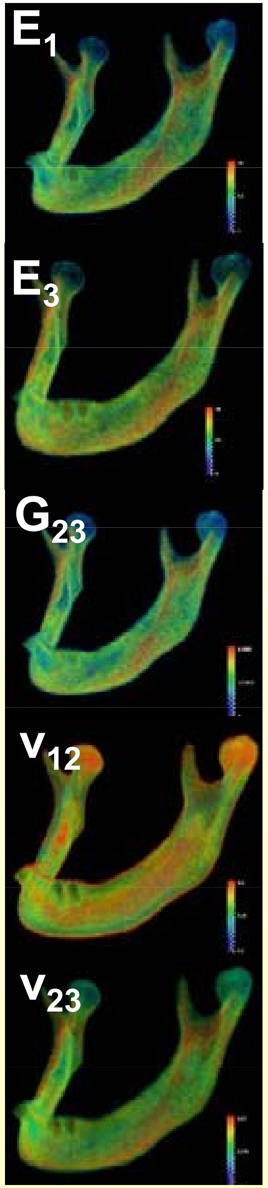
B.3 Realization for the simulation:

a) Calculation of individual orthotropic elasticity coefficients

Hounsfield values of the CT-data are related to **Bone Mineral Density**

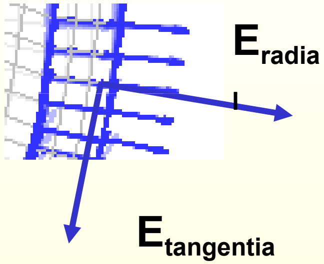


By a recent **micromechanical** approach of Hellmich and coworkers:



b) Assembling the anisotropic stiffness matrix

We assume locally orthotropic material symmetry defined by the anisotropic trajectories:

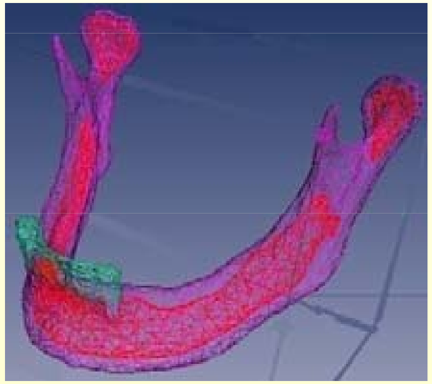


by the micromechanical approach of Hellmich et al

$\varepsilon_1 \quad 1 \quad \nu_{12} \quad \nu_{13} \quad 0 \quad 0 \quad 0 \quad \sigma$

orthotropic compliance matrix

For the simulation: transformation from the local coordinate system defined by the trajectories to the mandible's global coordinate system:



The result is a fully anisotropic compliance matrix.

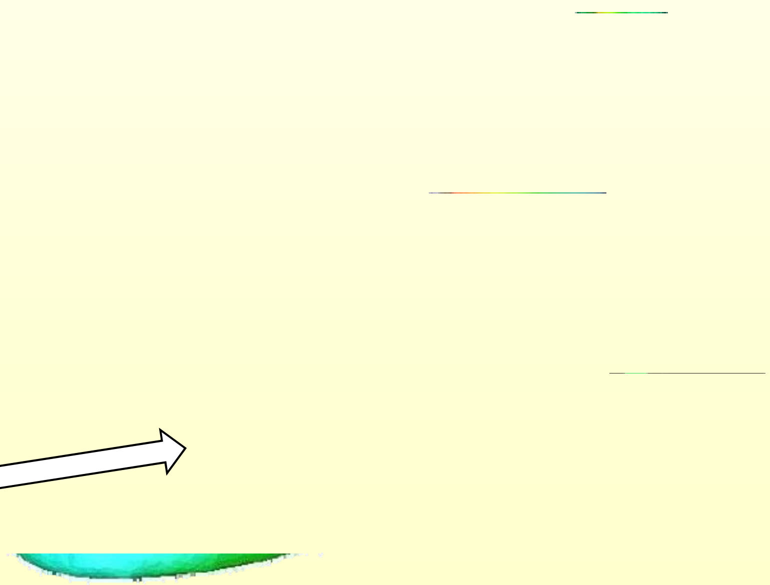
B.4) Chain of software tools and requirements

Step 0: CT-data of the mandible		
Step 1: Volumetric profile of the inner structure of the organ	Computer Graphics	Amira 5.2.2
Step 2: Identification of the inner skeleton	Biomedical Modeling, medical CAD	
Step 3: Reconstruction of the anisotropic trajectories	Biomedical Modeling	Own software
Step 4: Calculation of the inhomogeneous elastic coefficients	Micromechanics	Own software of C. Hellmich
Step 5: Calculation of the fully anisotropic stiffness matrix	Structural mechanics	Own software
Step 6: Finite Element simulation	Numerical Mathematics	Ansys, Kaskade

C) Results

Lateral bite on the leftmost premmolar

Consideration of the volumetric strain



Involved muscles::
M. temp.,
M. mass.,
M. pteryg. med.

unphysiological compression related partial dentition => atrophy of the alveolar ridge

FEM-tool: Kaskade,
B. Erdmann, ZIB, Berlin

Impact of Tissue anisotropy

Sensitivity analysis

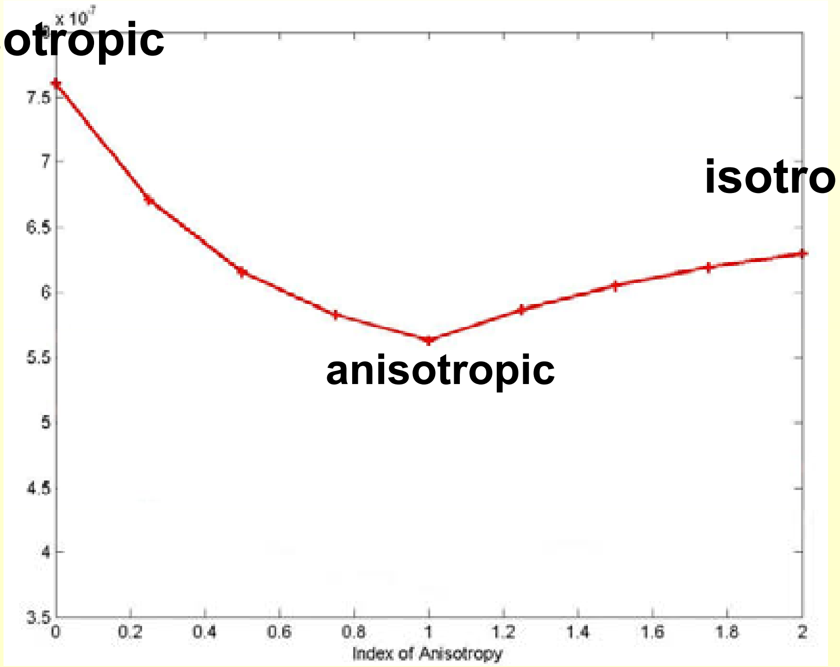
isotropic-soft | **anisotropic** | **isotropic-hard**

volumetric strain

Test of L_2-norm:

$$||\varepsilon||_2 := \left(\int \varepsilon^2 \, dx\right)^{0.5}$$

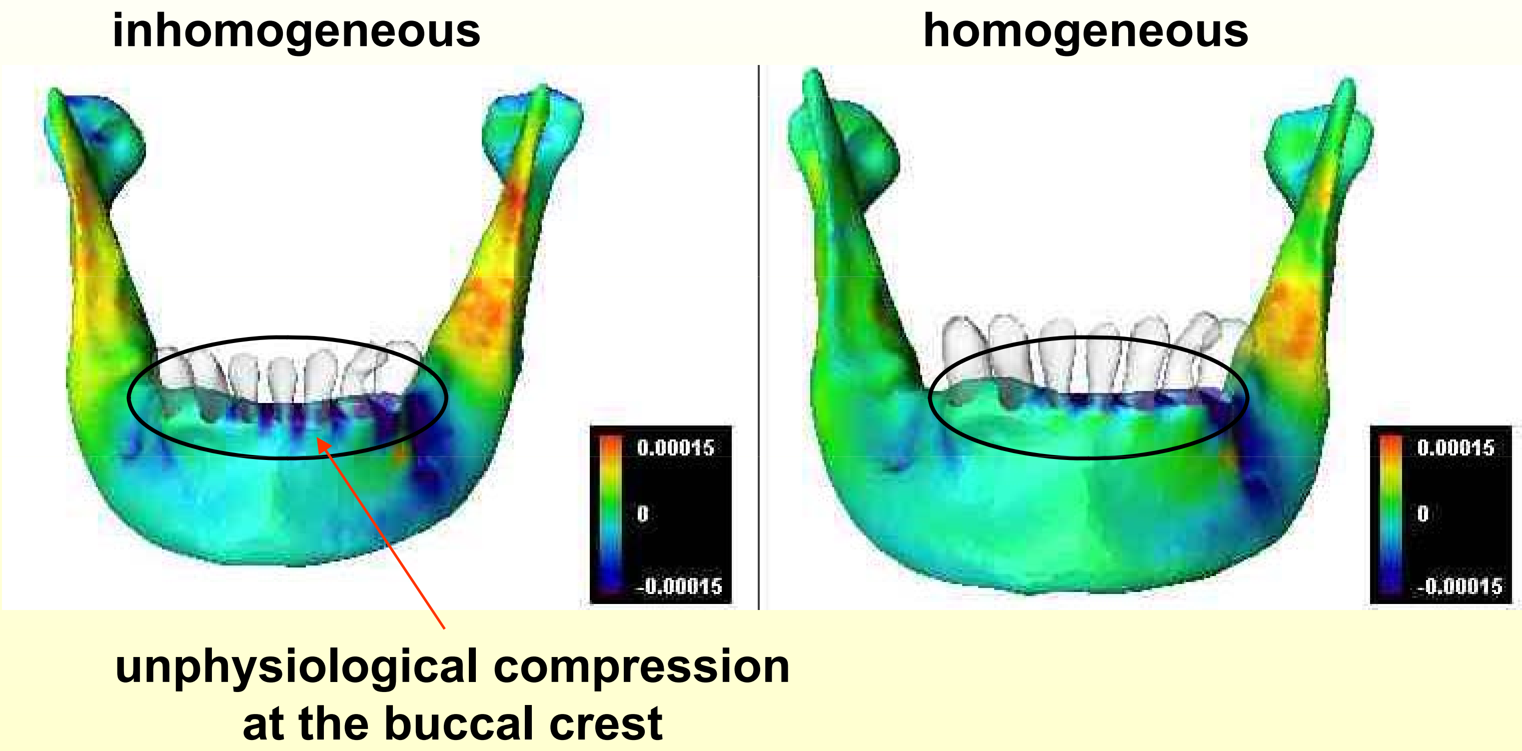
kind of minimization for the full anisotropic case



Tissue **inhomogeneity**

Comparison of volumetric strain due to a lateral bite on the leftmost tooth

- all fully orthotropic elastic coefficients, but ...



Comparison with the clinical situation: "buccal cortical bone loss"

D) Conclusion and Outlook

Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

From the engineering view:

We presented an approach for the introduction of tissue anisotropy to the FEM simulation for the human mandible.

Requirement for the FEM-solver:

There has to be the input possibility for a inhomogeneous, fully anisotropic stiffness matrix.

Actually under construction:

Reconstruction of the inner skeleton and also the anisotropic trajectories only based on a triangular surface of the organ.

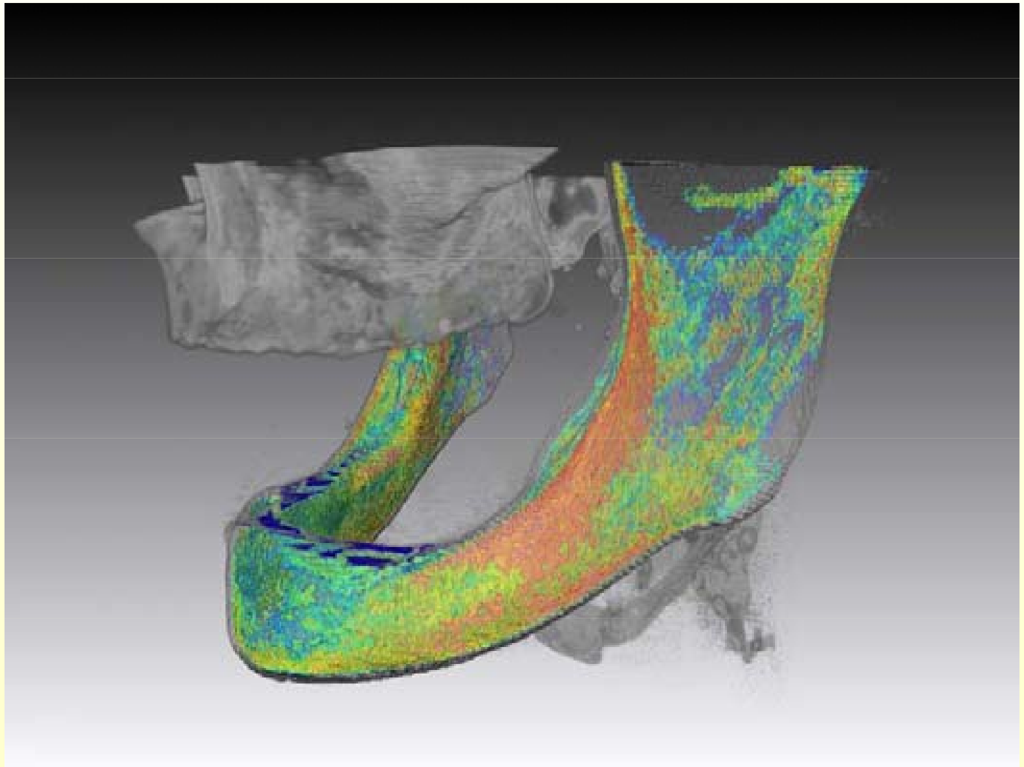
From the biomedical view:

We showed

- **qualitative relevance of material anisotropy within biting simulation**
- **anisotropy “spares” the jaw bone from loading**
- **some kind of optimality for anisotropy with respect to volumetric strain**
- **The opposite seems to be true for the inhomogeneity.**

Acknowledgements:

- Fujitsu Siemens Computers for supporting our research with computer equipment for effective 4D-Visualizations
- B. Erdmann for the possibility of the simulation by means of Kaskade



Thank you for your attention !