Experimental study and numerical simulation of the mechanical behaviour of the human mandible

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Introduction
Because of the complexity of the masticatory system, surgery of mandibular defects shows many complications. An interdisciplinary group of mathematicians, physicians and mechanical engineers is working in a joint project of the Sonderforschungsbereich 438 [Neff et al., 2000]. For support and mutual verification of numerical simulations, various in vitro experiments are done. Fig. 1 shows a scheme of the cooperation of numerical (in silico) and biomechanical (in vitro) tests. One of the crucial conditions for the whole project is the use of analytical equipment which is part of the daily medical routine.

![Figure 1: Mutual validation of numerical simulation and biomechanical experiments.](image)

A variety of biomechanical experiments are focussed on the mandible, but mostly only static weights and springs [Kroon et al., 1994] are used which means that the dynamic aspect of the masticatory system is disregarded. Also robotics [Wang et al., 1998] are a common method, but here merely teeth are tested, individually or in groups, or their prosthetic replacements respectively. The optimisation of implants like osteosynthesis plates requires the examination of the whole mandible.

Materials and Methods
With the objective to adapt the simulation step by step to the in vivo situation, a computer controlled test stand is used. The previously described machine [Schieferstein et al., 2000] consists of modular rig (holding test object and actuators), a 19"-rack (containing hydraulic control units and computer for general control and data acquisition) and a motion capture system (3 cameras and a computer). The hydraulic drives apply loads on the specimen (model or cadaveric mandible). Figs. 2a and 2b show the camera views on the specimen, the dorsal wires represent the masseter temporalis loops.
From a cadaveric human mandible, a CT scan and a plastic model were retrieved. A volume grid for the finite element simulation (Fig. 3a) was then extracted from the segmented CT data employing the commercial software package amira™. Based on a linear elasticity model of the mandible (for now taken as homogeneous and isotropic), the deformations for different load situations were calculated using our own FE environment FeliCs. The plastic model and the original specimen were used for biomechanical tests according to the numerical simulation. Using a video capture system, 4 points were tracked during the tests. To facilitate comparison with the numerical simulation, the specimens had to be fixated by plastering the condyles. Material parameters were then extracted by solving a nonlinear least squares problem.

Results
Given the nature of the cadaveric human specimen (osteoporotic mandible of an eighty year old male), tests were done for forces ranging from 50 to 90 N. Fig. 3a shows the location of the applied (equal) forces as specified for the simulation. The results of a simulation run are visualized in Fig. 3b, giving the absolute value of the deformation in each point for a specific load case. Concerning the material parameters, a least squares fit of the deformation in all measured points over the whole force range to the experimentally
determined values gave an elastic modulus of 3.4 GPa, while the Poisson’s ratio was taken from the literature as 0.33. It could be shown that the calculated displacements varied very little with the exact value of the ratio from the range of 0.3 to 0.35. Table 1 gives a comparison of the calculated and measured displacements of the four considered points.

Table 1: Calculated and measured shift of 4 points located at the ramus of the specimen.

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Discussion
The qualitative match between experimental and simulated data shows the viability of our approach. However, deviations (especially at the posterior points (PI and PS) on the ramus) show the necessity of further refinements of the mathematical model. The low calculated elastic modulus can also be attributed to the changes in mechanical behaviour caused by the process of preserving the mandible.

Tests have to be continued. Fixing, materials, and design of the implants will be modified in order to improve implant lasting and minimising their negative side effects such as bone necroses, damaged bone and nerve tissue, as well as their complicated handling.

As long as internal characteristics such as muscle and joint forces are unknown [Standlee et al., 1981], the required data for optimal implant design is missing. After an upgrade of the test equipment, software controlled chewing motions will be our approach to quantifying functional muscle forces.

References