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Validation of interdependency between inner structure visualization and structural mechanics simulation

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Introduction

Due to the interdependence of the inner architecture of bone and its functional loading already stated in the 19th century by Wolff, Roux and others, structural mechanics simulation of bony organs is of general medical and biomechanical interest. On the one hand, modern simulation techniques, mostly using finite element methods, enable reliable and efficient computation of stress and strain profiles and thus a detailed analysis of the loading situation of the considered organ. On the other hand, by means of visualization techniques developed by the group [3], a volumetric profile of bone mineral density based on CT numbers could be given.

Objectives

Our objective is to demonstrate this interdependence for the human mandible. This work is part of an interdisciplinary research project with the long-term goal to establish the mandibular simulation as effective means for planning and auditing craniofacial or orthodontic therapy. Because of the planned application in the clinical setting, validation and consistency of the underlying concept are essential. Furthermore, simulation efforts should be kept as small as possible. For individual biomechanical experiments in vivo are either impossible or very laborious we have to resort to other means. Motivated by the above cited fundamental interdependence we try to achieve qualitative correspondences of the volumetric 3D-profile representing the organ's inner structure and the simulated stress/strain results. Our general strategy is first to capture normal physiological loading situations of the mandible, then to explain pathological changes as atrophy of the alveolar ridge of an (partially) edentulous mandible, and finally to predict unwanted consequences of a planned treatment. By this, we hope also to contribute to computer orientated functional anatomy.

Material and Methods

In general, our simulation requires a representation of the organ's geometry, an appropriate material description, and a realization of the load case due to teeth or muscle and joint forces, see Figure 1. So, the simulation chain ranges from image processing of the computer tomography data for soft (esp. muscular) tissue segmentation up to specifically adapted post-processing of the simulation results. Reliability and efficiency of the simulation results are guaranteed by the adaptive finite element code KASKADE [2]. Besides the simulation itself, all reported programming and image processing steps have been created using Amira 3.1 - a system for advanced visual data analysis [1]. So, we are able to pursue a stepwise refinement of the simulation concept towards the desired applicability in the clinical setting.
Because of its beginning atrophy of the alveolar ridge and the disposability of multimodal data sets including CT-data, MRT-data, and anatomical photographs, we chose the mandible of the female Visible Human as simulation example [6].
Up to a strain limit of about 0.3 %, the material behaviour of bone can be described by linear elasticity. In most physiological situations, this value is not exceeded. Therefore, we refer to a linear anisotropic material law. Motivated by experimental evidence and biological arguments, we consider orthotropic symmetry of the bone tissue. Since the trajectories of anisotropic elasticity are not accessible from the CT data, they were reconstructed from the organ's geometry and from coherent structures which could be recognized from the spatial distribution of the CT values, see also [3]. Concerning the masticatory muscles, we tried to capture the physiological situation as far as possible. Again by means of visualization techniques described in [3], we extracted individual "lines of action" from the CT data. By a special algorithm, these lines were expanded to fanlike coherent vector fields similar to the anatomical reality. The temporomandibular joint was realized by two simplified joint capsules where the mandibular condyles were freely mobile. The capsules' bonding to the skull was modelled by rigid attachment.

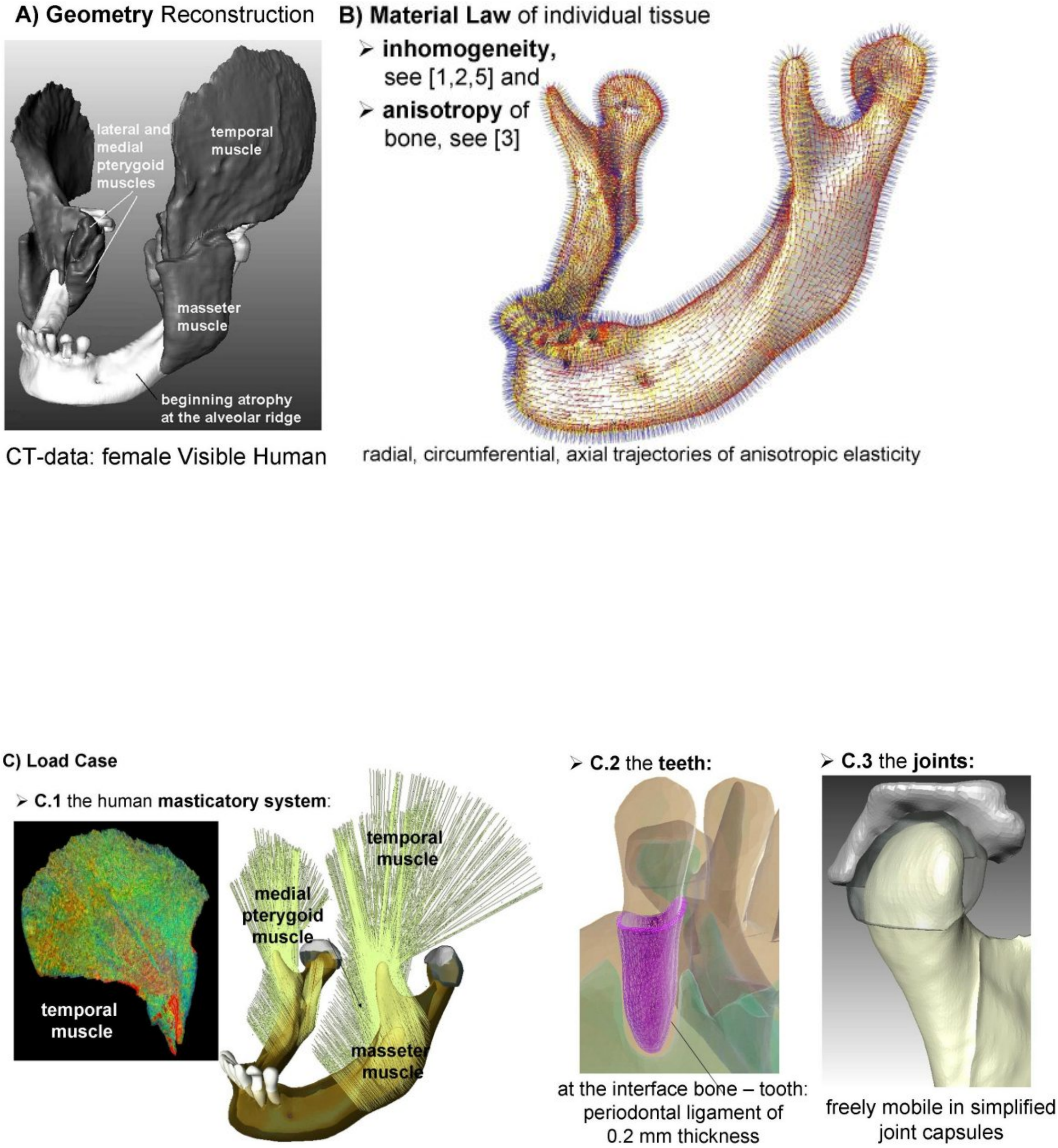
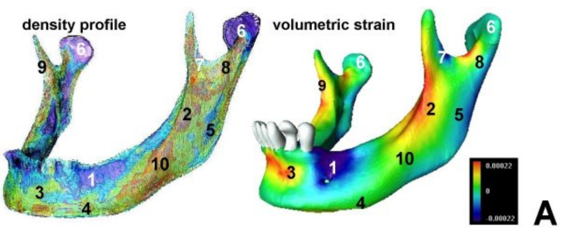
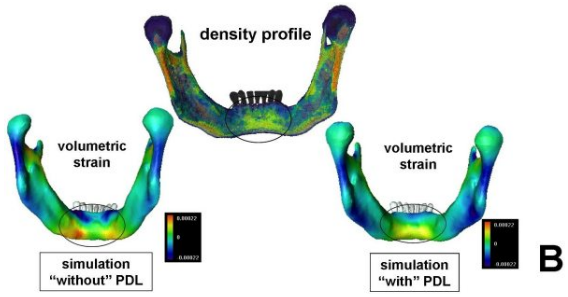


Figure 1: The prerequisites of the simulation which are a representation of the organ's geometry (A), an appropriate material description (B), and a realization of the load case due to muscle (C.1), teeth (C.2), and joint forces (C.3).

Results

We could state qualitative correspondences of the volumetric density profile of the jaw bone and the simulated stress/strain profiles. This means that regions of elevated stress respective strain were compared with regions of elevated tissue density and vice versa, see Figure 2. Especially, correlations of weakened regions of reduced density and elevated compression (negative strain) were studied. The first remarkable feature was a dominant compression at the alveolar process besides the biting tooth, see Figure 3. This corresponds to reduced density there. Next, we could state high dilatation at the mandibular notch, following the oblique line and the lower part of the coronoid process roughly correlated to elevated density in this region. At the condyles, low strain level is in qualitative agreement with low density. The same is true for the middle part of the mandibular ramus. For a more detailed discussion, we refer to [4]. Every step towards a more physiological model caused an enhancement of the qualitative correspondences between the density profile and the profile of simulated strain, see [5] for instance.





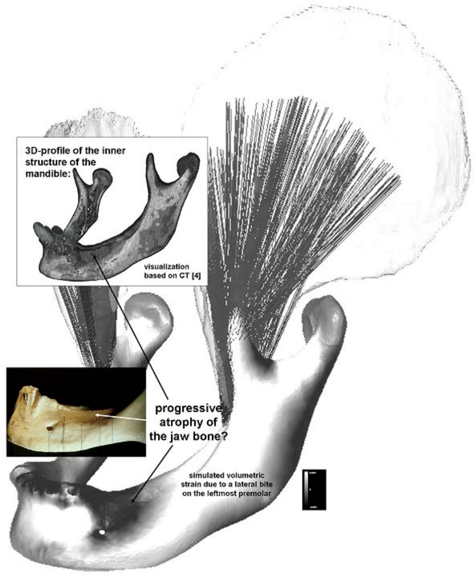


Figure 2: Qualitative correspondences of a density profile representing the organ's inner structure [3] and the simulated volumetric strain resulting to a bite on a very hard item, lateral view (A), dorsal view (B).

Figure 3: Dominant compression at the alveolar process besides the biting tooth in correspondence with progressive atrophy there, both simulated volumetric strain and density profile of the inner structure in grey scale coloration.

Conclusions

This study contributes to a vice versa validation of both, the simulation model and the density visualization techniques presented in [3]. In the long run, these observations may enable the use of this kind of simulation for diagnosis and prognosis. An important step will be the application to real cases stemming from the clinical praxis. From the point of biomechanics, these results indicate some kind of mechanical adaptivity of the organ.

Literature

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