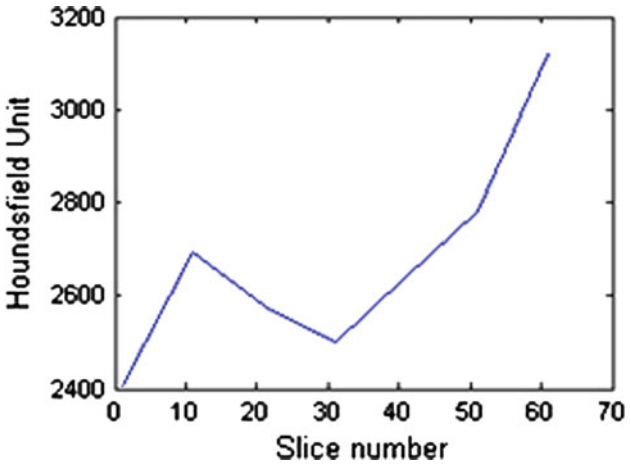

Fig. 2 Graph of the resulting threshold value plotted against the slice number. The threshold value for all slices can be interpolated from the graph

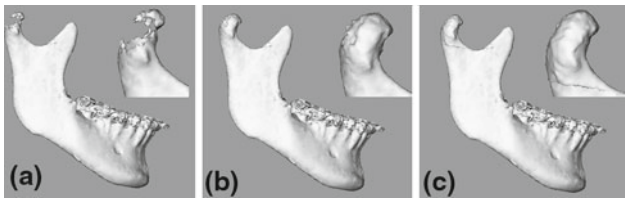

Fig. 3 **a** 3D rendered condyle using original CBCT dataset without image processing. **b** 3D rendered condyle using the semi-automated post-scan imaging enhancement protocol described by Xi et al. **c** 3D rendered condyle using the proposed local thresholding and 3D region growing algorithm

in the segmentation process. Following the completion of the 3D region growing process, the segmented surfaces of condyles were checked in ImageJ (National Institutes of Health, Besthesda, MA, USA). Small imperfections could be removed manually if necessary.

In order to assess the accuracy of 3D rendered condyles using the segmentation protocol as described above, the VOI's of the same 10 patients were segmented using the more labour-intensive post-scan imaging enhancement protocol described by Xi et al. [2] (Fig. 3). The segmented condyles of this control group were exported from ImageJ as '.tif' files and imported in MATLAB for further analysis. The Dice coefficient was calculated to evaluate the similarity of the 3D rendered condylar surfaces, where a value of zero would mean no overlap and a value of one a perfect match. Also the volume of each 3D rendered condyle was calculated.

The statistical data analysis was carried out with the SPSS software program, version 18.0 (SPSS Inc, Chicago, USA). Paired Student's *t* test and intra-class correlation coefficient (ICC) were used to analyze the reliability of volumetric measurements.

Results

The volume of segmented condylar process using the currently proposed protocol did not differ significantly to the control group (p = 0.20). The ICC coefficient for volumetric measurements between both groups was 0.94. The similarity between the semi-automatically rendered 3D condylar surfaces and the control group was excellent (Dice coefficient = 0.95).

Conclusion

The novel semi-automated approach for 3D rendering of condyles based on local thresholding and 3D region growing was shown to be accurate and reliable. It has significantly reduced the computing time in comparison to the previously used methods. The ease of use will further facilitate its implementation in the clinic and research setting, allowing accurate follow-up of the condyles following orthognathic surgery.

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Finite element simulation of a human mandible with an extended cystic lesion respecting tissue anisotropy and inhomogeneity

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Keywords Human mandible · Finite element simulation · Mandibular cyst · Anisotropy of bone

Purpose

Cystic or cyst-like lesions appear as kind of cavities within the bone, filled with fluid or mushy substance. Therefore, they presumably have serious weakening effect on the affected organ and decisive impact on the organ's biomechanical behaviour. Their treatment is subject of recent research.

This simulation study is focused on two concerns, firstly, an estimation of the influence of the apparent pathology on the mandibular biomechanics, secondly, an impression of the impact of bone tissue anisotropy and inhomogeneity on the simulation results. Though key features in biomechanical simulation, both tissue anisotropy and inhomogeneity cannot be accessed in sufficient detail until now. By the second author, a micromechanical model was developed for voxel-wise transfer of the Hounsfield values from CT-data to elasticity coefficients of mammalian bone. By the first author, a general concept for scientifically founded approximation of the anisotropic trajectories of elasticity was developed. Both approaches have already been successfully applied to a series of physiological mandibular cases.

Methods

We consider the case of a 42 years old female patient with an extended odontogenic cystic lesion. The mandible is partially edentulous and characterized by ongoing atrophy of the alveolar corpus on both sides.

As a more realistic modeling of the cystic fluid is currently beyond the scope of our study, we approximate it by negligible stiffness with respect to the surrounding bone. So, we assign zero stiffness to the mushy region plus some safety margin around it.

The cystic lesion was segmented from the CT-data with highly exaggerated safety margin. With regard to the voxel-wise interpretation of the grey values from CT, it is decisive that no voxel of the affected region is included to the model. The remaining mandibular

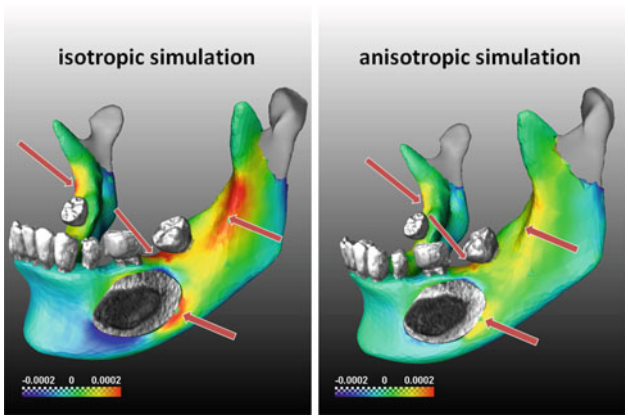

Fig. 1 Volumetric strain based on homogeneous elastic coefficients, from simulations with isotropic (*left*) and anisotropic (*right*) material properties

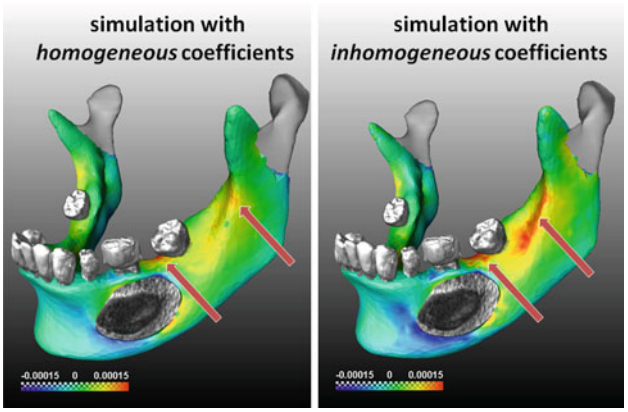

Fig. 2 Volumetric strain due based on anisotropic simulation, but with homogeneous (*left*) and inhomogeneous (*right*) material coefficients

tissue was reconstructed as a 3D-surface model and a tetrahedral finite element mesh was generated by state of the art techniques. As the preoperative CT-data were not covering the entire mandible, the condyles were added from post-operative data.

For the sake of a separate analysis of the impact of tissue anisotropy and inhomogeneity, we consider three variants of assignment of material coefficients (i) fully anisotropic and inhomogeneous according to the introductorily mentioned concept, (ii) anisotropic, but with homogeneous coefficients, so the spatial average of the of the distribution of the anisotropic elastic coefficients, and (iii) isotropic and homogeneous, with the axial (notably the highest) Young's modulus, and the mean of the anisotropic Poisson's ratios ν_13 and ν_23. As a simple and easily interpretable load case, we applied a moderate vertical force from above on the frontal part of the alveolar arch, i.e. on the incisors and partly on the canines. The load was applied in form of a homogeneous force density f = F/A, uniformly distributed over the loaded area A. It is known from previous simulation tests with other mandibles, that this load case gives significant insight into typical stress and strain states throughout the organ.

As the applied load is within the range of physiological loading human bone tissue can be modeled by a linear elastic material law. For finite element simulation, the toolbox Kaskade, ZIB Berlin, Germany, was used.

Results

Knowing from previous research, that volumetric strain is a valuable indicator not only for the organ's load carrying behaviour, but also for mechanobiological consequences of loading, we refer to these strains for an assessment of the lesion-affected mandible.

For all three variants of the simulation, the lesion induces strong asymmetric effects in the strain distributions, especially around the tooth located in the upper right of the lesion, as shown in the Figs. 1 and 2. For demonstration purpose, teeth and cystic region are rendered by direct volume rendering. As the condyles are added from post-operative CT-data they are omitted from the interpretation.

A comparison of anisotropic and isotropic simulation with homogeneous coefficients shows highly reduced strain for the anisotropic configuration for both tensile and compressive strain component (Fig. 1). Notably, this effect is more dominant at the affected side than at the healthy one.

In the opposite, the introduction of material coefficients respecting full tissue inhomogeneity and anisotropy resulted in elevated volumetric strain (Fig. 2). The asymmetry in the distribution of strains is even more pronounced rather than in simulations focusing on tissue anisotropy only (Fig. 1). Again, this effect concerns both tensile and compressive strain. High tensile strain can be observed at the mandibular ramus and between the leftmost molars at the affected side of the mandible, whereas major compressive strains prevail at the cystic boundary near the bottom of the alveolar arch, as well as at the incisors and part of the canines.

Conclusion

The prevalence of the cystic lesion produced a highly asymmetric load carrying behaviour of the affected mandible, independently how detailed the simulation reflected the individual tissue configuration. The comparison of the anisotropic and the isotropic simulation with homogeneous coefficients reveals that the introduction of tissue anisotropy seems to spare the mandible from excessive straining which is in agreement with the earlier results for physiological cases. Notably, the pathology even endorsed this effect. In contrast, the introduction of inhomogeneous coefficients respecting local X-ray attenuation/mass density distributions resulted in an elevated loading of the mandible. Interestingly, the observed regions of tensile and compressive strain peaks somehow correspond to regions with reduced Hounsfield values.

As we expect new insight in possible interdependence between the biomechanical behaviour and the healing progress future research will be dedicated to further refinement of the simulation model and the analysis of additional pathological cases.

Acknowledgments

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Development of three-dimensional graphic viewer software using game controller device and medical image displaying

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Keywords Medical graphic viewer · 3D acceleration sensor · 3D virtual space

Purpose

Three-dimensional (3D) virtual space is recognized by some ubiquitous devices in the world of computer games and various entertainments. Nintendo Wii® Remote Plus (Nintendo, Kyoto, Japan) is the wireless controller of Wii®, and some sensors (3D acceleration and near infra-red for positioning) and interfaces (Bluetooth) are installed. 3D acceleration sensor enables to work as a