Beating instead of Biting: Finite Element Analysis for Cranio-Facial Traumatology

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Summary

Though intensive academic and commercial research, the surgical treatment of cranio-facial or mandibular trauma is still a challenge. Due to sometimes severe complications, fractures of the temporomandibular joint (TMJ) are a special focus. This article gives a resume of the current activities of the group in the application of structural mechanics simulation by means of finite element method to traumatologic cases in oral and cranio-maxillofacial surgery. The simulated stress / strain profiles resulting from a virtual impact were analyzed and compared with the real situation by means of clinical observation and radiographic images. By a sensitivity analysis, it was evaluated whether clenched teeth in combination with stretched masticatory muscles may protect the TMJ from injury. By means of the special stress or strain distribution through the injured organ, we hope to gain a better understanding of the condition of the bone tissue around the lesion which will contribute to improved treatment planning. Additionally, the project is expected to be of benefit for protection devices and optimised behaviour with regard to special sports or vocation. Finally, there are possible applications in forensic analysis.

Keywords

human mandible; finite element simulation; trauma; fracture of the mandible; biomechanics

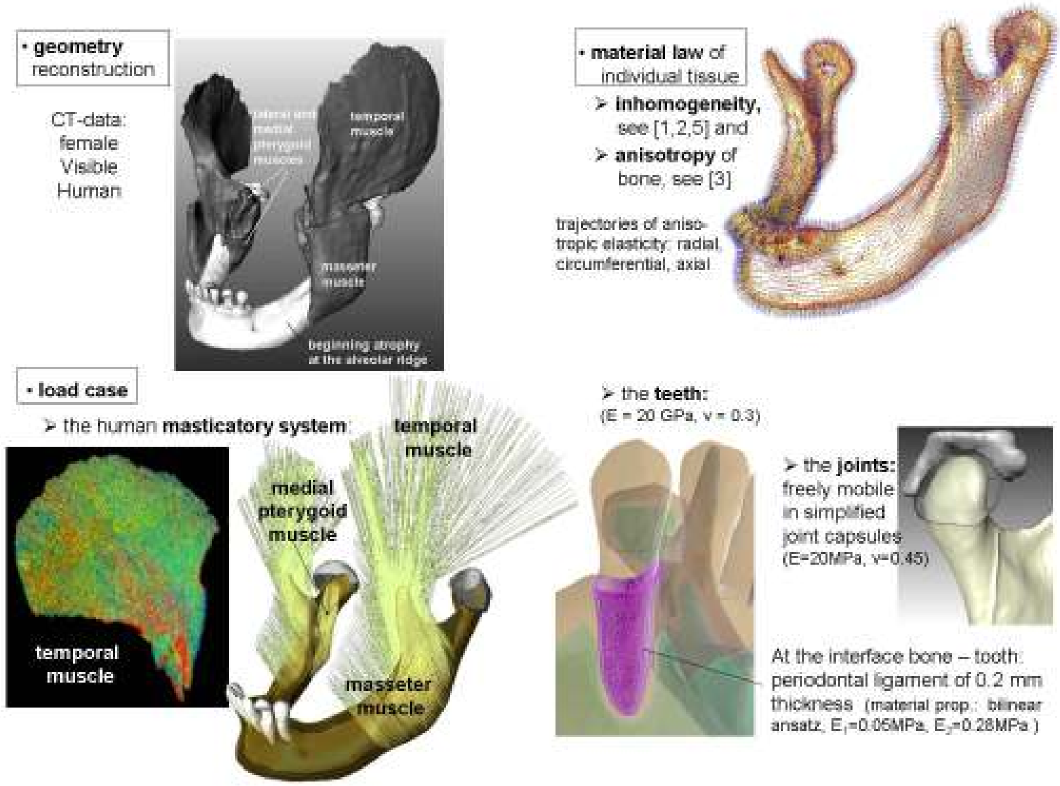


Figure 1: Overview of the preprocessing of the mandibular finite element simulation consisting in a) geometry reconstruction of the considered organ, b) definition of the inhomogeneous and anisotropic material law of bone, and c) realization of the load case due to muscle, joint, and teeth forces.

1. Introduction

On account of the fundamental adaptation of bone according to its funtional loading, structural mechanics simulation is of high relevance in the biomedical field. In classical mechanical engineering, however, one of the major benefits of structural analysis is detection and prevention of failure. This aspect also applies to clinical cases of trauma where unphysiological loading – either accidentally or on purpose, as by a hook to the chin for instance – often causes considerable failure.

Though remarkable progress within the last decades, the treatment of cranio-facial or mandibular fractures is still a highly discussed topic in oral and cranio-maxillofacial surgery. The possible traumatologic scenarios are characterized by high variability.

This article is a resume of the current activities of the research group in finite element simulation of cranio-maxillofacial trauma cases [6, 10-12]. The expected benefit consists in a better understanding of the concerned cases. Actually focused aspects are the effect of the impact with respect to the activity of the masticatory system and the special role of the dentition. Direct applications are surgery and therapy planning, but also forensic evaluation, as well as optimised behaviour and protection devices for special sports or vocation. The presented work is part of a detailed research project concerning the structural behaviour of the human mandible with the mission of a stepwise refinement of the simulation towards the anatomical reality in combination with a concise discussion of relevance and impact of the considered features [8].

The article is structured as follows. In the next section, a parametric platform for simulation of the mandibular structural behaviour under physiological loading is presented. In the next but one section, this platform will be extended to unphysiological load cases. This is followed by section 4 where simulation results will be given. Section 5 is dedicated to a short introduction of a related study based on clinical trauma cases. Finally, in section 6, a brief discussion and outlook is provided.

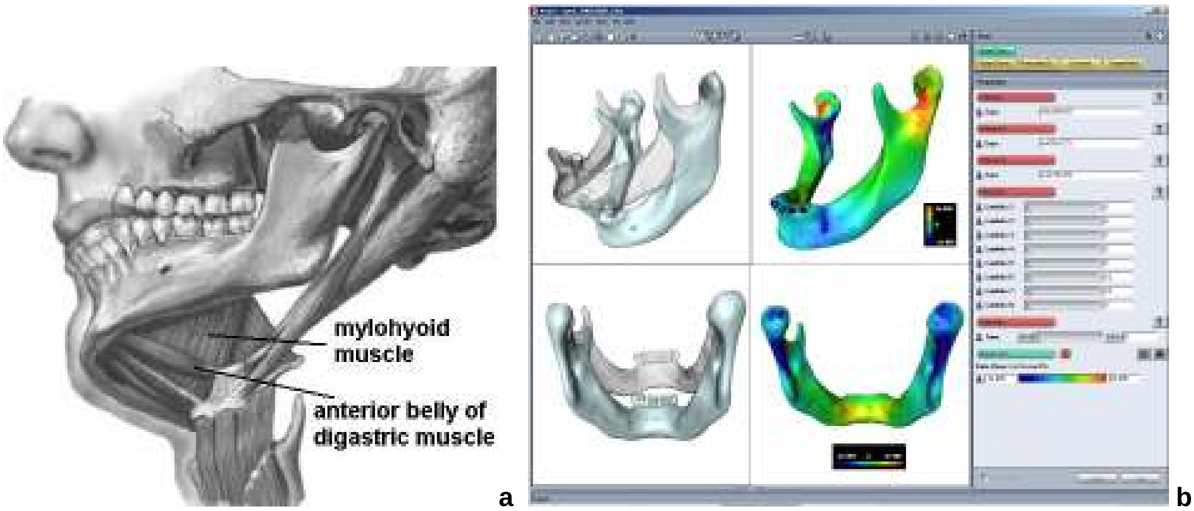


Figure 2: a: Anatomical drawing of mylohyoid and digastric muscles (mouth openers) [13], b: screenshot of the platform, simulation of the activity of these muscles, left: displacement (100-times exaggerated), middle: volumetric strain, right: user input [9].

2. Parametric platform for finite element simulation of the human mandible

In biomechanical simulation, external forces due to muscles or other extraneous causes are decisive input parameters. In this context, detailed sensitivity analysis proved to be appropriate means for better insight. In [9], an approach for a parametric platform for finite element simulation of a human mandible for easy and fast testing was presented (Fig. 2 b). Based on user input of the absolute values of muscle and biting forces, the respective stress / strain profiles are calculated based on a linear superposition of previously simulated “basic solutions”. So, for structural analysis, no additional finite element simulation is needed. Thereby, even refined sensitivity analysis can be performed within short time.

The mathematical background is as follows. Up to a strain limit of 0.3 which is not exceeded in most physiological loading conditions the material behaviour of bone can be described by linear elasticity. For finite element analysis, the governing partial differential equation $\mathrm{div}(\sigma) = 0$ (σ: stress tensor) is transformed to a matrix equation $A\,x = f$ where f depends linearly on the input forces for the case of no inhomogeneous Dirichlet boundary conditions. In this case, solutions of this mathematical problem referring to different input forces can be combined by linear superposition. So, a set of simulations was performed each related to only one external force component other than zero, a non zero left masseter muscle force for instance. Further, simulations referring to biting forces applied to occlusion points on the teeth were performed. For the calculation of a simulation result referring to a special combination of muscle and bite forces, these “basic solutions” are ro be linearly superposed. Reliability and efficiency of the procedure were guaranteed by the adaptive finite element code KASKADE [15].

As each of the underlying simulations had to be performed only once it was possible to use a very refined finite element model (Fig. 1). Full dental anatomy including Periodontal Ligament could be included. Recent micromechanical developments, driven forward by the third author [2-4], in combination with macroscopic research on the organ level [8] allowed for translation of a CT data set into inhomogeneous and anisotropic elasticity tensors [5]. The temporomandibular joint was realized by simplified joint capsules whose bonding to the skull was modelled by rigid attachment. For details of the simulation concept, see [8]

Figure 3: Realization of the masticatory muscles.

Within the platform, the following oral and masticatory muscles can be addressed:

- masseter muscles
- medial pterygoid muscles
- lateral pterygoid muscles
- temporal muscles
- mylohyoid muscles
- digastric muscles

By means of visualization techniques developed by the group, individual muscle fibre directions were extracted from CT data [7]. By a special algorithm, the fibres were expanded to coherent vector fields (Fig. 3). The (absolute) force value provided by the user produces some special scaling of this vector field. Additionally, x-, y-, and z-components of biting forces applied to occlusion points on the teeth were provided. Finally, the application was realized within an Amira 4.x network [1, 14]. Besides stress and / or strain profiles, the system displays the organ's deformation which can be exaggerated by a user defined factor. See Fig. 2 b for the effect of mouth opening muscles on mandibular displacement and volumetric strain.

3. Extension of the platform to traumatologic situations

On the contrary to the preceding section where physiological load cases as biting were analyzed, the concept of the simulation platform will now be applied to unphysiological load cases due to violent impact [10]. As this platform is an extension of the previous one the same very refined finite element model has been used including dental structures as the Periodontal Ligament and so on. As the previous platform, the application was realized within an Amira 4.x network [1, 14]

In traumatologic situations, the strain limit of linear elastic behaviour of bone is certainly exceeded. Nevertheless, the occurring stress/strain profiles may be interpreted as qualitative failure indicators. Actually, the user has the choice of an increasing number of regions on the mandibular surface where the injury can be launched at. Power and direction of the impact force vector can be set arbitrarily (Fig. 4).

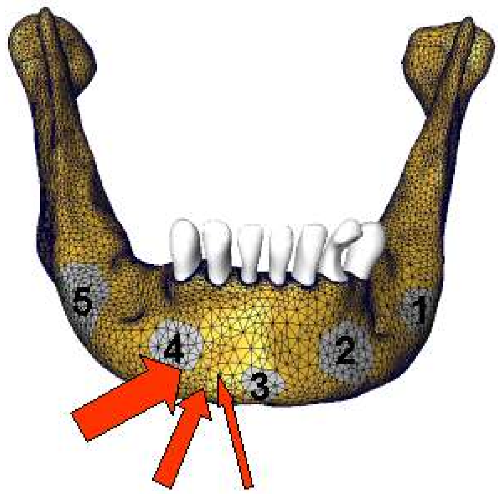


Figure 4: 5 regions on the mandibular body to the user's choice where the injury can be launched at.

As before, the masticatoy system including the both digastrics and the mylohyoid muscles can be activated. The same is true for arbitrary forces on the teeth simulating "clenched teeth during fighting". For this purpose, forces on teeth crowns (which are in reality in contact with the teeth of the upper jaw) were chosen in a way that the muscle forces were compensated as much as possible, and upward or downward movement of the mandible was prohibited.

With regard to the high significance of volumetric strain in bone remodelling and resorption, the previous platform provided mainly profiles of this post processing variable. On the contrary, for the evaluation of traumatologic situations, a failure indicator is needed. The classical post processing variable for this purpose is the von Mises equivalent stress. Therefore, we also exploit the von Mises equivalent stress in our new version of the platform (Fig'.s 5 a, 6 a). But, it is well acknowledged that the von Mises equivalent stress is more for isotropic material as steel rather than for anisotropic tissue as bone. Therefore, in the actual part of the study, high compressive or tensile strain was additionally considered as failure indicator (Fig'.s 5 b, 6 b). These indicator variables can be easily replaced by any other appropriate post processing variable as the strain energy density or the principal shear stress / strain.

4. Application of the trauma platform

In the course of the project, various tests have been performed. Special focus was put on an evaluation of the role of the masticatory muscles in combination with clenched teeth which turned out to be decisive for the overall load carrying behaviour of the organ subjected to trauma situations. If the masticatory muscles were stretched and the teeth were clenched the stress / strain profiles were qualitatively changed [11, 12].

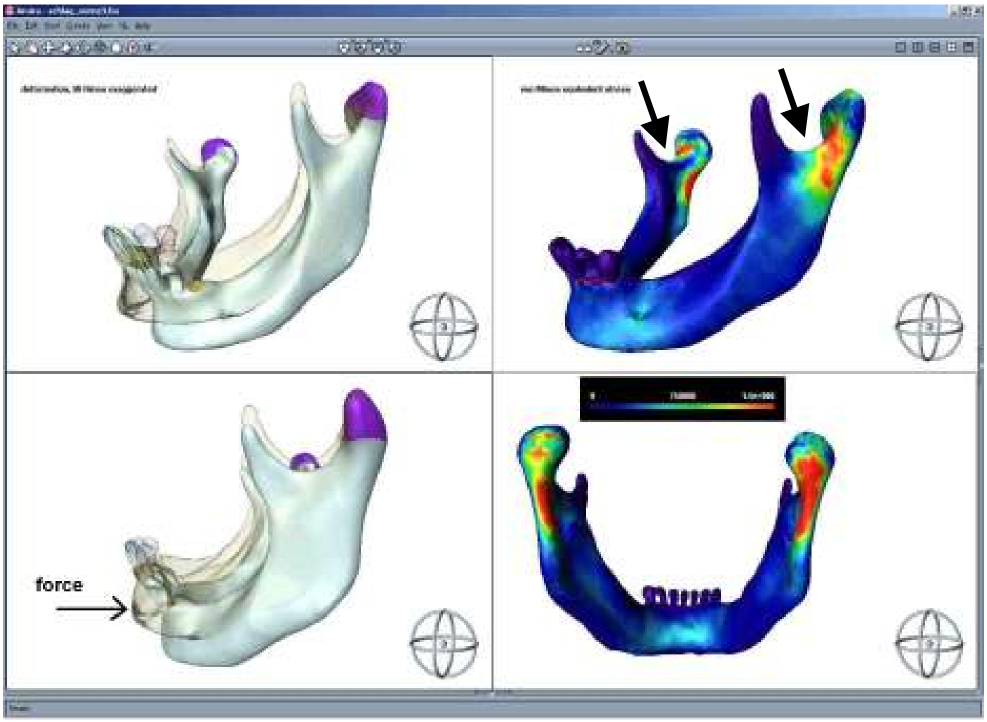
In [11], the role of the masticatory muscles in combination with clenched teeth for the sake of protection of the temporomandibular joint (TMJ) was analyzed in detail. As regards the question whether, by clenched teeth, the TMJ may be protected from high (unphysiological) compression, the simulation results indicated that the answer depends on the order of magnitude of the applied force as well as on its direction. By a blow from below, perpendicular to the alveolar plane, the condylar neck was affected independently whether the teeth were clenched or not. This observation may be corresponding to a situation where a person falls down on his or her chin. On the contrary, if the blow's angle towards the alveolar plane was more and more decreased the situation changed and the simulation results suggested that teeth clenching would well provide remarkable protection of the TMJ. Notably, fractures of the TMJ are still a challenge in cranio-maxillofacial surgery. So, their avoidance is highly appreciated.

5. Blinded study based on clinical radiographs

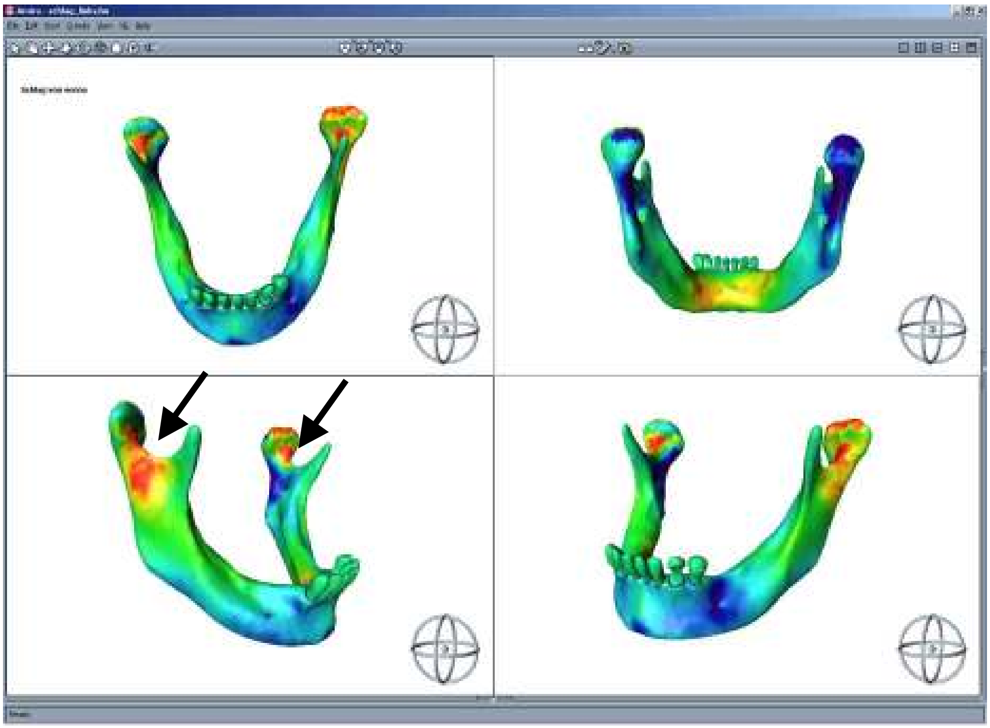
For the sake of validation of the significance of the approach, we started a blinded study where traumatologic cases given by clinical radiographs are to be "resimulated" [10-12]. This means that a simulation scenario (placement, direction, and absolute value of the force of the blow within the platform) has to be found which results in maximal stress / strain values at the location of fractures whereas the other parts of the mandible should be significantly less loaded. See Fig. 7 for an exemplary result where a deep fracture of the neck of right mandibular condyle was "resimulated" by an ipsilateral impact on the alveolar body [12]. Additionally to the radiographs, the simulation results were discussed in the context of the clinical experience where interesting agreement was found.

The cases tested until now showed that, by means of finite element simulation, qualitative correspondences of stress / strain profiles and traumatologic situations could be observed. Clinical cases given by radiographs could be "resimulated" in a sense that a simulation scenario could be found characterized by maximal stress / strain values at the location of fractures. Certainly, a bundle of simulation scenarios may "reproduce" the fractures shown in the respective radiograph. So, we do not claim a full specification of the background situation. But, the method is exepcted to contribute by the elimination of the scenarios not matching the given fracture locations [12].

Notably, the mandible where the actual tests were performed is partially edentulous and affected by beginning atrophy of the alveolar ridge whereas the patients' mandibles shown on the radiographs had all kind of dentition. In spite of this fact, the qualitative results referred in the preceding sections could be achieved which underlines the general character of the analysis. Nevertheless, this finding encourages further research based on further (dentate) mandibles for the sake of again more detailed results.

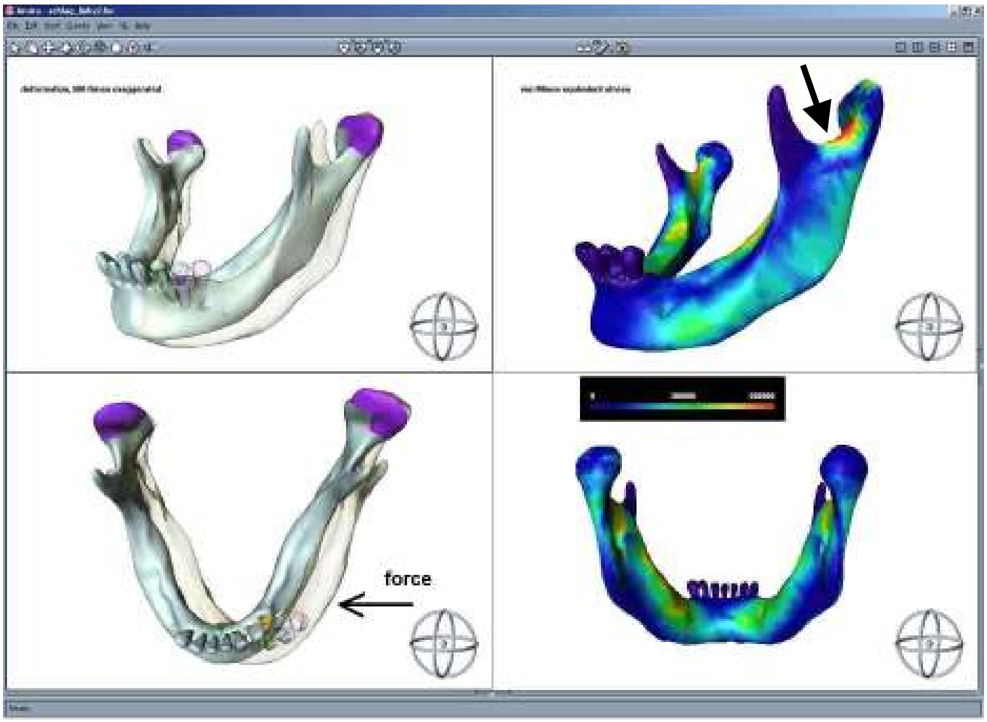


a) Evaluation of the displacement and the von Mises equivalent stress

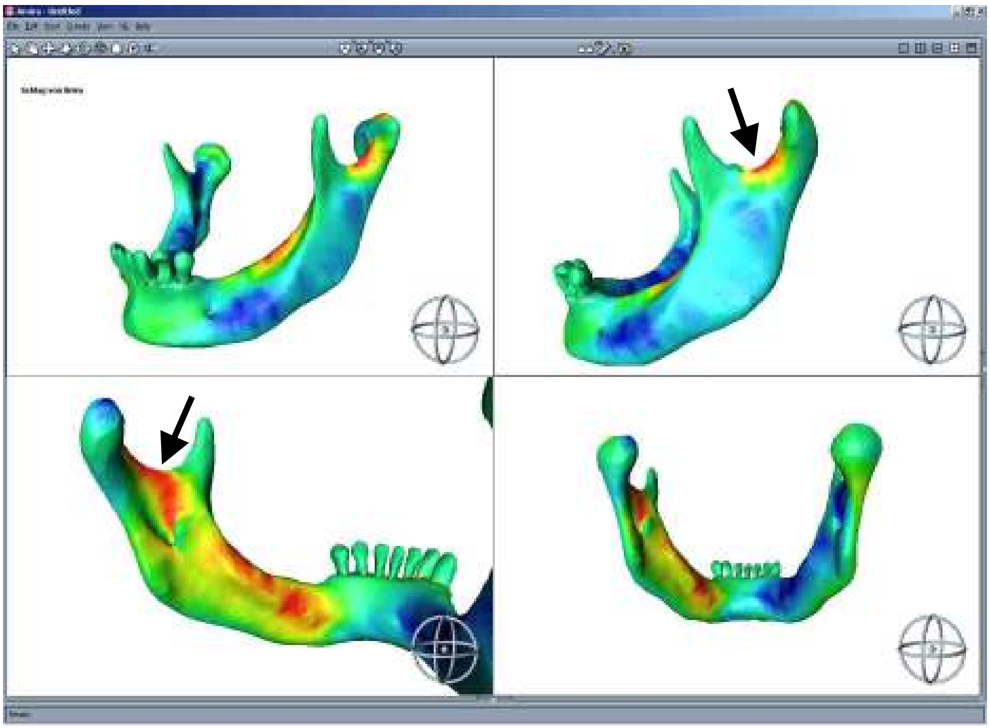


b) Evaluation of the volumetric strain

Figure 5: Application of the trauma platform to the evaluation of a hook to the chin. Both condyles are subjected to high von Mises stress as well as to high tensile strain, see the black arrows in the figures.



a) Evaluation of of the displacement and the von Mises equivalent stress



b) Evaluation of the volumetric strain

Figure 6: Application of the trauma platform to the evaluation of a blow from the left. The left condyle is subjected to high von Mises stress as well as to high tensile strain, see the black arrows in the figures.

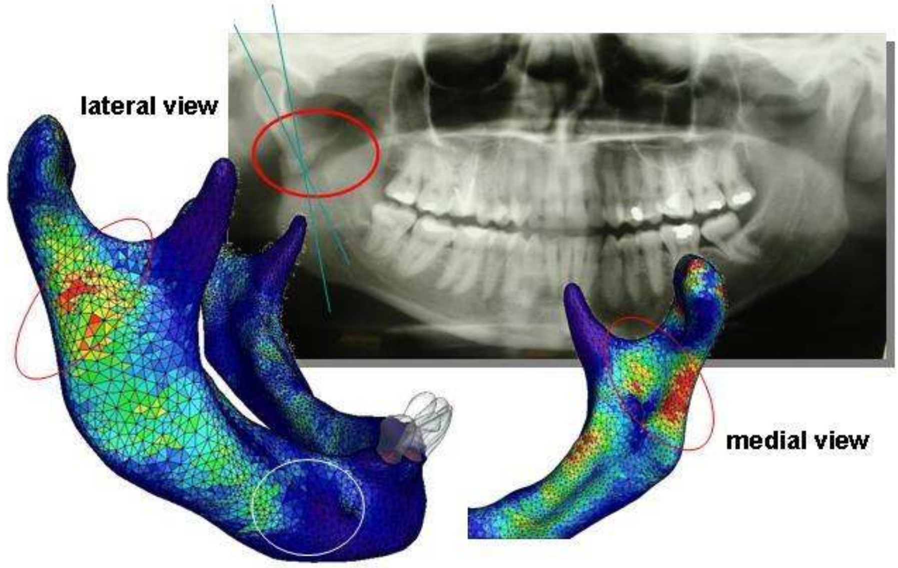


Figure 7: "Resimulation" of a clinical case given by radiograph showing a deep fracture of the right condylar neck: maximal von Mises equivalent stress can be observed at locations similar to the fracture [12].

6. Discussion and outlook

The approach is expected to provide valuable input for the design of protection devices and for optimised behaviour with regard to special sports or vocation. For forensic analysis, we expect that the method will contribute by elimination of scenarios not matching the given fracture locations. One might assume the situation without stretched muscles and clenched teeth as related to an unexpected blow whereas clenched teeth and stretched muscles are more likely for a person aware of the dangerous situation. As mentioned before the project is not aimed at a full specification of such kind of situation.

Nevertheless, the immediate purpose of our approach is a better understanding of the injured organ's condition. Fractures of bone as an adaptive biological tissue are supposed to fundamentally differ from mechanical failure in engineering. A lot of our trauma simulations showed increased stress / strain values around the fracture leading to the suggestion of weakened bone there. This finding was confirmed by surgical observation.

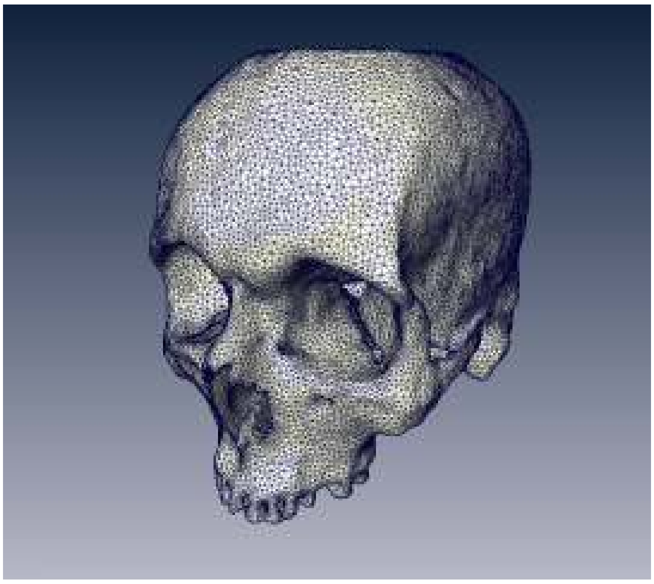


Figure 8: Tetrahedral finite element mesh of a skull comprising about 735.000 elements.

Future work will be dedicated to evaluation of the dentition in the case of injury. A next step will be resimulation of traumatologic situations of the skull, namely of the zygomatic arch. First test simulations have already been successfully performed. In Fig. 8, a tetrahedral finite element mesh comprising about 735.000 elements is shown. It was generated by the built in Amira mesh generation algorithm [1, 14].

7. References

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