



*Finite element simulation, biomechanics,  
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## **GENERAL PROJECT'S SETUP FOR FINITE ELEMENT SIMULATION OF BONY ORGANS DEMONSTRATED FOR THE CASE OF A HUMAN MANDIBLE**

Due to high complexity of biological tissue, the requirements of biomechanical finite element simulation differ from those inherent to projects in conventional computational mechanics. Especially, pre- and post-processing are of increased impact. For the sake of a valuable application of the simulation results in the clinical setting, a highly multidisciplinary method of operation is recommended. The purpose of this paper is a short description of a general project's structure of a biomechanical finite element project. The focus is on examination of bone as an organ where the case of a partially edentulous human mandible was taken as simulation example.

### **1. INTRODUCTION**

The interdependence of its load carrying behaviour and the inner architecture of bone is one of the most discussed principles of biomechanics. Thanks to its generally accepted outcome in structural mechanics, finite element simulation has become a tool of high interest in the research of this field. From computational mechanics, a rich body of literature is available. Nevertheless, there are fundamental differences between biomechanical finite element simulation projects and projects stemming from mechanical or civil engineering for instance. Therefore, this article is dedicated to a short description of a general project schedule within biomechanical simulation especially for the examination of bone as an organ, see also [13]. Notably, the structural analysis of "bone as an organ" as the human femur or the mandible differs from the examination of "bone as a material" as described in [2] for instance.

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## 2. METHODS

In general, a finite element project can be structured into three major parts which are the pre-processing, the numerical computation, and the postprocessing of the results, see Table 1. Within

preprocessing, the necessary input for the simulation has to be provided which is again structured according to the three keywords geometry reconstruction up to generation of finite element mesh, material law respectively material properties, and the load case. The numerical computation is the core of the project. Finally, the postprocessing of the computed results is dedicated to their significant interpretation in order that the simulation will benefit the application it was originally motivated by. These three parts can be looked at a cycle with the mission of continuously improving the outcome of the simulation. Up to there, a biomechanical finite element project does not differ from common finite element simulation in structural mechanics.

In the following, the three major parts – preprocessing, numerical simulation, and postprocessing, see Table 1 – will be described with special focus on biomechanical simulation demonstrated for the case of a human mandible. Because of its general accessibility, the partially edentulous mandible of the female Visible Human, characterized by beginning atrophy of the alveolar ridge, was chosen as simulation example [14]. The geometry reconstructions from 3D image data and all visualizations were performed by means of the visualization toolbox Amira 4.0 see [1] or [15].

2.1. Pre-processing	A) Geometry: <ul style="list-style-type: none"> <li>○ surface reconstruction</li> <li>○ volumetric finite element mesh generation</li> </ul>	B) Tissue properties with regard to <ul style="list-style-type: none"> <li>○ inhomogeneity</li> <li>○ anisotropy</li> </ul>	C) Load case due to <ul style="list-style-type: none"> <li>○ muscles</li> <li>○ joints</li> <li>○ further influence as teeth or outer forces</li> </ul>	
2.2. Simulation	<ul style="list-style-type: none"> <li>○ constitutive modelling (special linear or nonlinear material law)</li> <li>○ numerical computation</li> </ul>			
2.3. Post-processing	<ul style="list-style-type: none"> <li>○ choice of the appropriate postprocessing variable</li> <li>○ significant visualization</li> <li>○ biomedical interpretation</li> <li>○ validation</li> </ul>			

Tab.1 General structure of a biomechanical finite element simulation project.

## 2.1. THE PREPROCESSING

Following the first row of Table 1 the preprocessing consists in (A) generation of finite element mesh based on the individual patient's anatomy, (B) an implementation of a material law, and (C) a realization of the load case due to forces acting on the considered organ, see the sketch given in Fig. 1. Starting with geometry reconstruction human anatomy is highly irregular compared to usual geometries coming from CAD (Computer Aided Design).

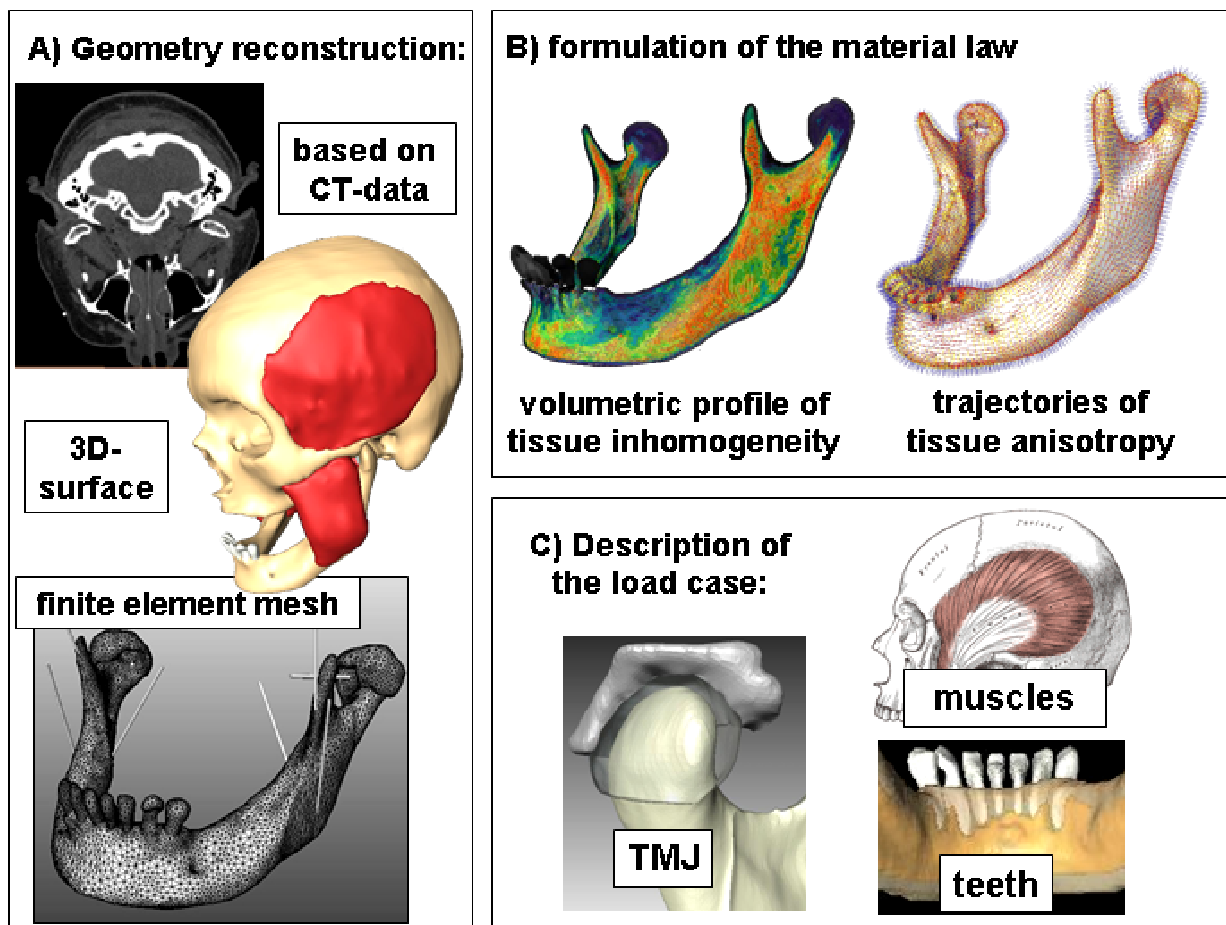


Fig.1 Overview about the three parts of preprocessing of mandibular finite element simulation: geometry reconstruction/finite element grid generation, implementation of an acceptable material law, and realization of the load case.

The mandible's 3D-reconstruction is based on Computed tomography (CT) data where image processing, segmentation, and 3D-surface reconstruction are preparatory steps [7]. In this way, the individual geometry is quite well reproduced and a triangular surface mesh sufficient for volumetric grid generation could be generated (Fig. 1 A). Up to a strain limit of 0.3 which is not exceeded in most physiological conditions, the material behaviour of bone can be described by linear elasticity. Generally, the information about tissue inhomogeneity can be derived using patient's CT data [3,4]. As regards tissue anisotropy, other sources of knowledge have to be referred to as experimental

evidence for instance. See [8] for a mandibular approach. The third step within preprocessing concerns the load case. By default, we can add muscle and joint forces which means the temporomandibular joint for the considered case, see Fig. 1 C and Fig. 2. The mandibular condyles were embedded into simplified temporomandibular joint capsules where they are somewhat freely mobile [11]. Concerning masticatory muscle forces, individual "lines of actions" were reconstructed based on an approach developed by the group taking into account different portions showing rather heterogeneous activity as the temporal muscle for instance [11]. Besides muscle and joint forces, within mandibular biting simulation, if so partial dentition has to be realized. Easiest way are forces applied to the tooth crown. See [8] for more sophisticated approaches.

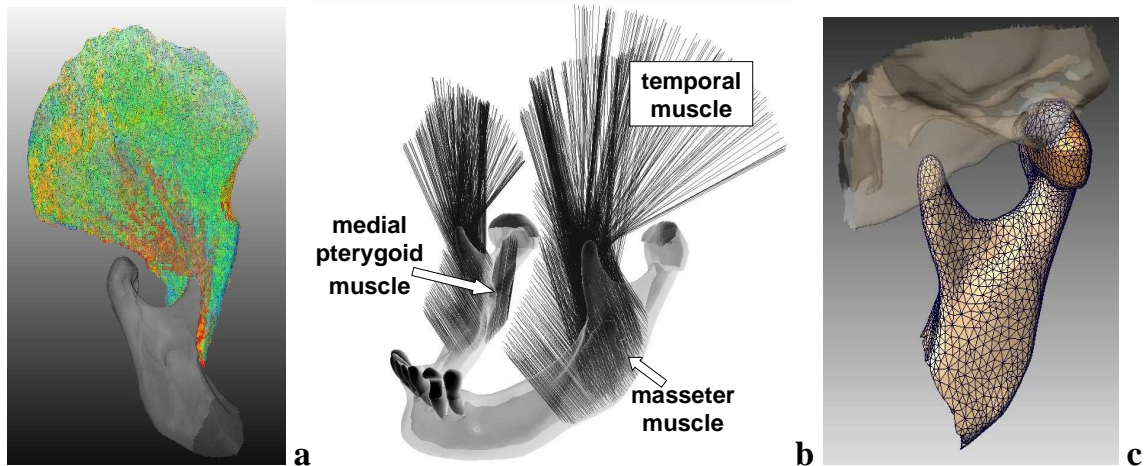


Fig.2 Visualization of the temporal muscle (a), inhomogeneous vector fields representing the masticatory muscles as input of the simulation (b), realization of temporomandibular joint (c).

## 2.2. THE NUMERICAL CALCULATION

Once the choice of material law e. g. linear/non-linear respectively further more sophisticated material approaches (see second row of Table 1) will have been provided the numerical simulation can be performed. The key requirements are "reliability" and "efficiency" which mean, on the one hand correctness, and on the other hand by acceptable simulation efforts. For the mandible simulation, we applied the adaptive Finite Element code KASKADE [6]. Within this approach, estimates of the discretisation errors, local grid refinement, and multilevel techniques guarantee the wanted impact of the method.

## 2.3. THE POSTPROCESSING

Whereas in conventional computational mechanics of mainly isotropic materials, the von Mises equivalent stress was proven as valuable failure criteria biomechanical simulation requires another strategy. Due to its significance in bone remodeling, the evaluation of volumetric strain allowed significant conclusions for a lot of applications [8]. Within the framework to the porous media, further valuable postprocessing variables are currently discussed [4]. Independently from the chosen post processing variable, significant visualization of the simulation result is of decisive impact for correct interpretation in the biomechanical and/or biomedical context. For the latter, tight cooperation with the medical doctors is advised which again gives a difference from conventional

engineering projects. Finally, the validation of both, the simulation results and their interpretation closes the project cycle.

### 3. RESULTS

The simulation results –see Fig. 3 for a lateral bite on the mandible – have to be discussed with regard to the respective medical application. The success of simulation depends on whether the question posed at the beginning could be fully or partially answered. The applications in man-

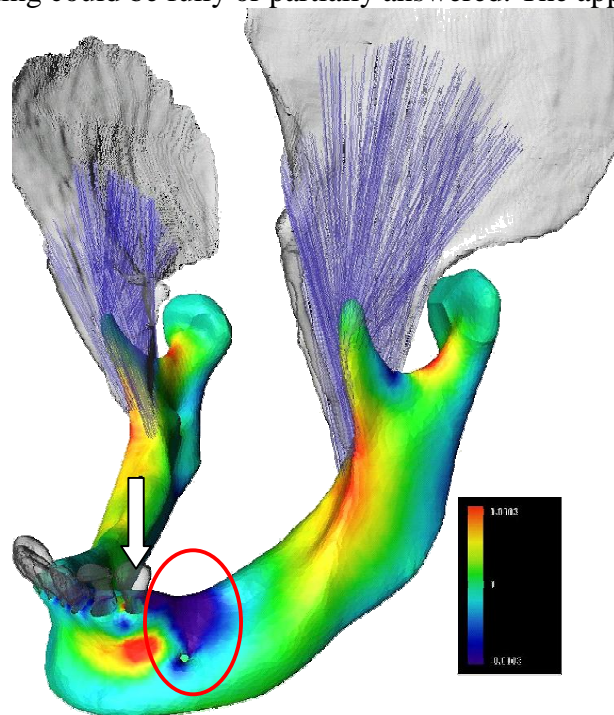


Fig.3 Simulation result: volumetric strain due to a bite on the leftmost premolar (arrow), temporal muscle including muscular lines of action in transparent rendering, unphysiological compression due to partially edentulous biting.

dibular simulation concern the very common atrophy of the alveolar [7] ridge (see also Fig. 3), the condition within the temporomandibular joint [10], or influence of dental anatomy, especially the periodontal ligament on the overall load carrying behaviour [9]. The interpretation and validation has been done by means of a volumetric profile based on the grey values from CT [12] or in comparison of the simulated teeth with the simulation of dental implants [9]. A classical validation approach in structural mechanics is simultaneous mechanical tests and simulation. As regards human bony organs, this is nearly impossible to be performed in vivo.

### 4. DISCUSSION

To start with the biomechanical results have to benefit the medical practice which renders a multidisciplinary method of operation beyond engineering as essential. This multidisciplinary is not limited to the cooperation with the medical doctors. For biomechanical structural mechanics simulation requires much higher complexity of the pre- and post-processing compared to standard engineering simulation various input from computer science is strongly needed. Examples are image

processing for the segmentation, 3D-surface reconstruction, smoothing and simplification of triangular surfaces, and sophisticated visualization techniques for pre- as well as for post-processing.

A further important difference to standard finite element projects in engineering is a changed view of accuracy. Whereas geometry reconstruction of acceptable quality is in the mean time achievable by special toolboxes the inhomogeneous and anisotropic distribution of elastic coefficients over the organ is still very unclear. The same is true for the boundary conditions, namely those due to muscle or joint forces. By this, the biomechanical simulation cannot be expected to provide results of the same quantitative reliability.

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