Modelling of temporomandibular joint and FEM analysis

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The purpose of this paper is to develop a new complete replacement of the temporomandibular joint (TMJ). A three-dimensional finite element model of the temporomandibular joint has been developed according to the CT data. The model consists of a half skull, a half mandible and a temporomandibular joint disc. Stress analysis of TMJ during normal occlusion was carried out using non-linear finite element analysis (FEA). The model consists of 54 758 elements and 16 665 nodes. Material properties were obtained from previously published data and were considered to be isotropic and linear. Contact surfaces were defined between the temporomandibular disc and the mandibular condyle and between the temporomandibular disc and the fossa eminence on the skull. Between contact surfaces a finite sliding was allowed. Stresses in the TMJ components (disc, mandible condyle and the fossa eminence on the skull) were obtained. The results have shown stress distribution during normal occlusion.

Key words: temporomandibular joint, finite element model, replacement surgery

1. Introduction

The question of facial and jaw replacement surgery is very extensive, complex and requires a lot of effort in order to work out and implement new curative procedures and to renew the function and shape of orofacial area with respect to the patient.

From the anatomical and biomechanical points of view, temporomandibular joint (TMJ) is sophisticated bicondylar articulatory complex with great demand on neuromuscular control with a frequency of motion indicated up to 2000 periods per

day. This makes the TMJ one of the most frequently exerted joints of the human body and in conjunction with individual uniqueness of this joint places high demand on its design and reliability.

The goal of the project is to conduct an intensive research in order to develop a new complete TMJ replacement. Temporomandibular joint replacement is very sophisticated and must be specially designed for each individual patient.

Experimental studies concerning the distribution of the loads in the TMJ have been performed on animal models. The number of such studies is limited, because it is difficult to implement experimental devices, such as strain gauges, into the joint and not to cause damage to its tissues without influencing their mechanical behaviour. Mathematical models of the human masticatory system including the TMJ were found as a powerful tool to predict the loads acting on this joint. However, many studies have oversimplified the geometry of the TM disc. Therefore, the tissue deformations and the distribution of loads inside the joint could not be analyzed properly.

Numerical modelling can provide the understanding of the joint physiology and also pathogenesis of the joint diseases. Application of the finite element stress analysis technique is ideal for the biomechanical investigation of the TMJ. Although finite element analyses of TMJ were carried out by many authors [1], [3], [7], in the analyses, some simplifications were made. Problems of all FE analyses are definitions of the muscle forces, movement of the TM disc during jaw opening and material properties of the temporomandibular disc. Some analyses were created as 2D contact problems or even analyzed without contact. The results of these analyses were affected by the boundary conditions and complexity of the models.

Therefore it was necessary to create a complex three-dimensional model of TMJ as global system of the skull, mandible, TM disc, ligaments and muscles. Contact interactions were defined between the TM disc and the fossa eminence of skull and between the TM disc and the mandible condyle. All ligaments and muscles which participate in occlusion were used in this model.

2. Materials and methods

2.1. Geometry

The geometry of the model was obtained from the head of embalmed male cadaver, showing no abnormalities, using a CT scans. Muscles and ligaments were additionally modelled into the CAD program according to the anatomical knowledge. The task is symmetrical, therefore only halfs of the skull and mandible were used and that was significant simplification of the FE analysis. Geometrical model of the TMJ is shown in figure 1.
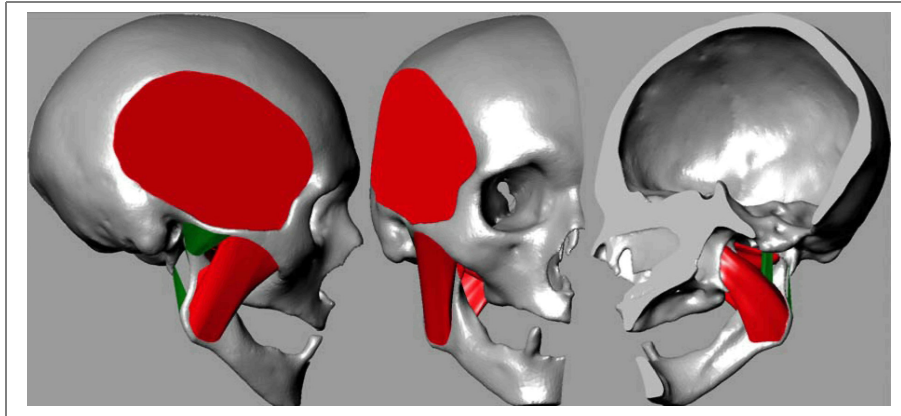
Fig. 1. The geometrical model of skull and mandible

2.2. FE model

Model of the TMJ was exported from the CAD program into the automated mesh generator NETGEN, where four-noded tetrahedral elements for the skull and the mandible were generated. The TM disc was meshed by eight-noded brick elements in the TrueGrid® mesh program. Finally, muscles and ligaments were defined by connector elements. This special element allows various definitions of the material properties, loading forces and the element behaviour. For this application, a connector element of axial type was used. This type provides a connection between two nodes where the relative displacement is along the line separating the two nodes.
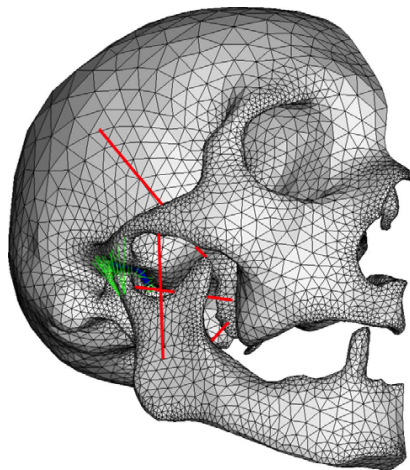
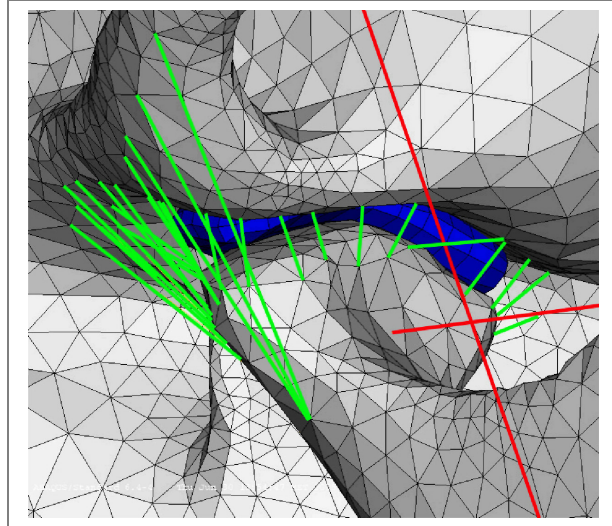

Fig. 2. FE model of skull, mandible and the TMJ

Fig. 3. Detailed FE model of the TMJ; muscles (connector elements),
ligaments (connector elements) and TM disc are shown

Ligaments and muscles represented by the connector elements were connected to the mandible and the skull by distributed coupling constraints. This coupling represented muscle insertion into the bone. The coupling constraint provides coupling between a reference node and a group of nodes. The constraint distributes loads, so that the resulting forces at the coupling nodes are equivalent to the forces and moments at the reference nodes. The FE model of the TMJ is shown in figures 2 and 3.

The FE analysis was defined as a nonlinear contact task and solved in ABAQUS 6.5.1 (Hibbit, Karlsson, Sorensen, Inc., Providence, RI). Contact interactions were defined between the TM disc and fossa eminence on the skull and between the TM disc and the mandible condyle. All contacts were defined as surface to surface slide contacts. The coefficient of friction for articular surfaces is unknown. It was estimated that the coefficient of friction must be smaller than 0.15 because of the lubrication with a synovial fluid. The coefficient of friction f was estimated to be 0.08.
The FE model consisted of 180 eight-noded tetrahedral elements, 54578 four-noded tetrahedral elements, and 48 connector elements. Total number of nodes was 16 665.

2.3. Material properties

Data on the material properties of all TMJ skull parts were taken from previously published data. The cortical and cancellous bones of the skull and the mandible were considered to be isotropic and linearly elastic. Tooth and ligaments were also defined

as isotropic and linearly elastic. As the range of magnitude of TM disc material properties in published data is wide, Young's modulus and Poisson's ratio were estimated and given in table 1. The TM disc was also defined as homogeneous and isotropic. All material properties assigned to the structural elements are listed in table 1.

Table 1. Material properties of the TMJ components

Material	Young's modulus [MPa]	Poisson's ratio [−]
Cortical bone	16300	0.31
Cancellous bone	960	0.3
Ligaments	1200	0.28
Tooth	19000	0.3
TM disc	16	0.45

2.4. The forces applied and boundary conditions

Advantage of using connector element lay in the possibility of applying the resulting forces directly. Geometrical parameters are fully defined by the muscle insertion between two bones. A normal jaw occlusion was used for this analysis and forces were applied in connector elements. All forces were assumed to be symmetrical and had equal magnitude on the right and left sides of the mandible. Magnitudes of all the forces applied were taken from published data [2], [8].

Symmetrical boundary conditions were applied to the sagittal surfaces of the skull and the mandible. The base of skull was firmly restrained and tooth displacement in the *z*-direction was constrained in a normal jaw occlusion situation. All the forces applied are listed in table 2.

Table 2. Muscle forces corresponding to normal jaw occlusion

Muscles	Force [N]
Lateral pterygoid	378.0
Medial pterygoid	191.4
Temporalis	528.6
Masseter	340.0

3. Results

The results illustrated the stress distributions in the TMJ during a normal jaw occlusion. The stress distributions obtained based on this model are given in figures 4,

5 and 6. High von Mises stresses occurred in the mandible near the processus coronoideus. The maximum von Mises stress was about 5.5 [MPa].
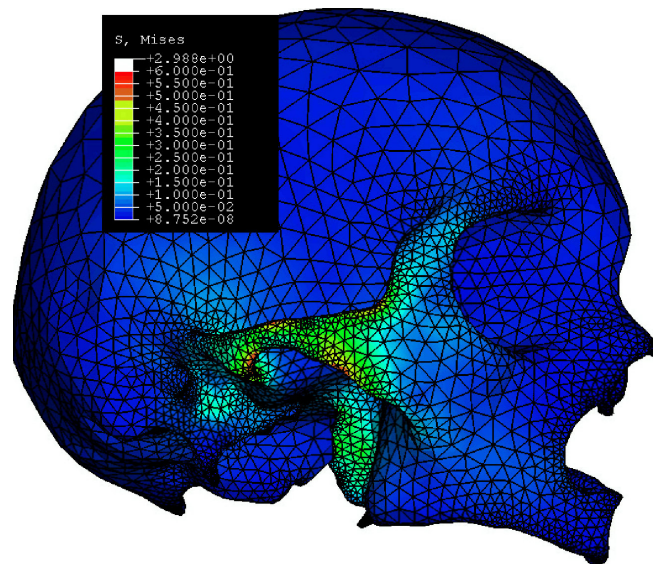

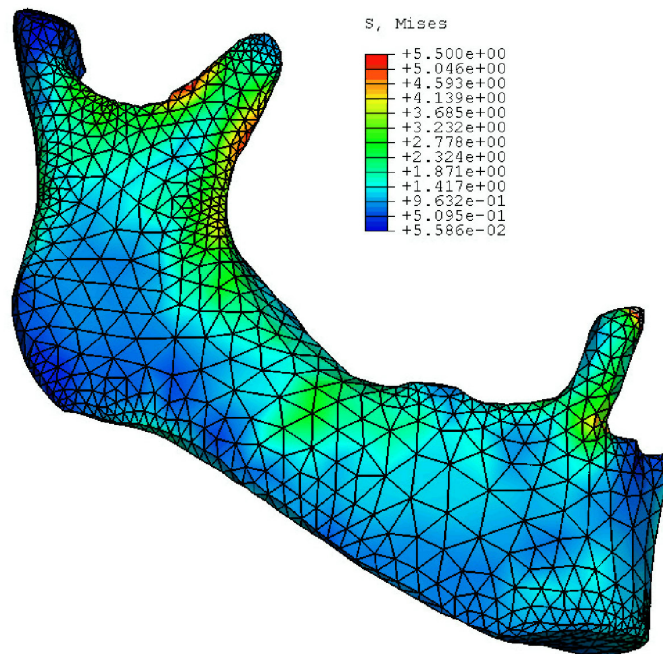Fig. 4. Distribution of the von Mises stresses in the skull [MPa]

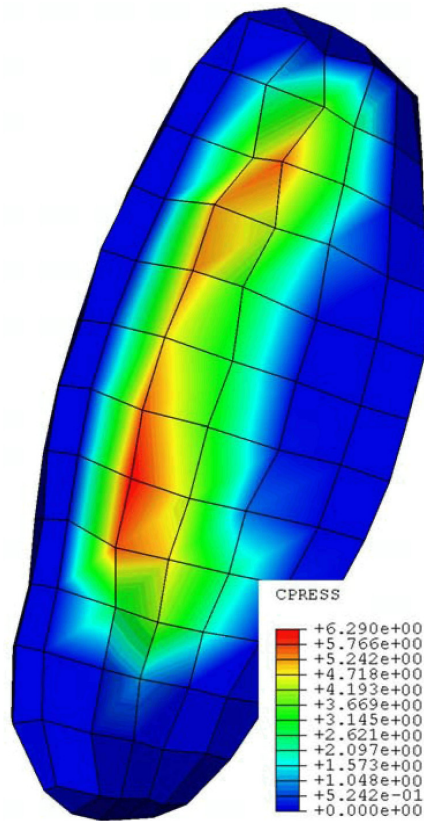Fig. 5. Distribution of the von Mises stresses
in the mandible [MPa]

Fig. 6. Distribution of the contact pressure [MPa]
in the TM disc

Maximal von Mises stress occurring on the skull, whose value approached 3 MPa, arose in the arcus zygomatius, were m. masseter is connected with the skull. High contact pressure was measured at the contact surface on the mandibular surface of TM disc; the contact was defined between the TM disc and the mandible. The maximum contact pressure was about 6.3 [MPa].

The forces in the ligaments were quite small, and reached the maximum values in the joint capsule (0.3 N).

4. Discussion

The project describes a three-dimensional model of the temporomandibular joint. All parts of the TMJ were shaped according to its anatomical geometry which was sampled with high resolution.

Material properties of the joint components were considered to be isotropic and linear in this analysis, so that it can provide preliminary results. In the next analysis, it is intended to collect a detailed information about the material behaviour, especially about the TM joint disc, and to improve the final output.

Stresses in the joint components (disc, mandibular condyle and fossa eminence on the skull), all TMJ ligaments and muscles have been analyzed during a normal jaw occlusion. The TMJ kinematics is very sophisticated as the joint movement includes shift rotations in ordinary jaw closure. There are also several more complex movements, e.g. shear, performed by the TMJ joint. Loading of the TMJ is non-symmetrical due to chewing, and the stress maximum is on the side of the oral cavity opposite the food.

In the Laboratory of Biomechanics at CTU in Prague, the kinematics of TMJ is studied. 55 volunteers with no abnormalities and without prosthetic replacement have been measured during chewing common food (rolls) and hard food (almonds, peanuts) with three stationary digital cameras. The activity analysis method was used to reconstruct the trajectory of the mandible movement. The aim was assign a number of contacts of occlusal surfaces (occlusion) during chewing process of one bite, amplitudes of the movement during chewing and the directions of the movement. We intend to import this data into this FE model.

During the jaw opening the TM joint disc slides slightly and then it is pulled by muscle, so that it is not easy to describe it. The movement of the TM disc was studied according to MRI scans where the adjustment of the sequence and the field of view is very important and complicated to set. Finding a solution to the question will surely approach the TMJ model to the real joint.

5. Conclusions

The model used is suitable for modelling physiological state of the TMJ. The results of this analysis will be used for the development of a new total TMJ replacement. Material properties and loads could be tested experimentally in order to verify model.

Acknowledgement

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