FEM ANALYSIS OF THE TEMPOROMANDIBULAR JOINT

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Abstract: The purpose of this project is to develop a new total replacement of the temporomandibular joint. 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 performed using non-linear finite element analysis. The model consists of 54 758 elements and 16 665 nodes. Material properties were obtained from published data and were considered as 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, 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.

Introduction

Facial and jaw replacement surgery problematic is very extensive, complex and requests a lot of effort in order to elaborate and implement new curative procedures and renew the function and shape of orofacial area with respect to the patient.

From the anatomical and biomechanical point of view, temporomandibular joint (TMJ) is sophisticated bicondylar articulatory complex with high requirements on neuromuscular control with a frequency of motion indicated up to 2000 periods per day. This makes the TMJ one of the most frequently loaded joint of the human body and in conjunction with individual uniqueness of this joint places high requirements on its design and reliability.

The goal of the project is a beginning of a large research work on a new total TMJ replacement development. Temporomandibular joint replacement is very sophisticated and must be designed for each individual patient.

Experimental studies regarding the distribution of the loads in the TMJ have been performed in animal models. The number of experimental 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 influences to 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 properly analyzed.

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

Therefore it was necessary to create 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 skull - fossa eminence and between the TM disc and the mandible condyle. All ligaments and muscles which participate in the occlusion were used in this model. Normal occlusion position was used for the verification of the function and the application of this model.

Materials and Methods

Geometry: The geometry of the model was obtained from the head of embalmed male cadaver, showing no abnormalities, using a CT and MRI scans. Muscles and ligaments were additionally modelled in to the CAD program according to the anatomical knowledge. Only half of the skull and mandible were used for

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simplification of the FE analysis. Geometrical model of the TMJ is shown in Figure 1.

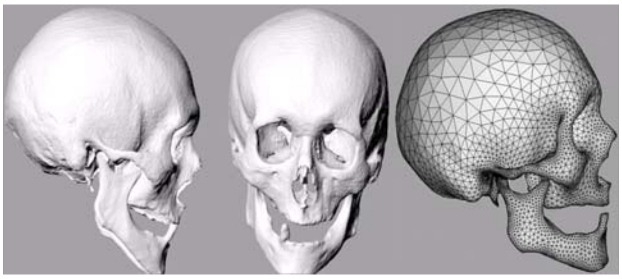

Figure 1: The geometrical model of the skull and the mandible

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 into 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, axial type was used. This type provides a connection between two nodes where the relative displacement is along the line separating the two nodes. It represents discrete physical connections such as axial springs, axial dashpots or node-to-node (gap-like) contact. The axial connection does not constrain any component of relative motion. The available component of relative motion u acts along the line connecting the two nodes and measures the change in distance separating the two nodes.

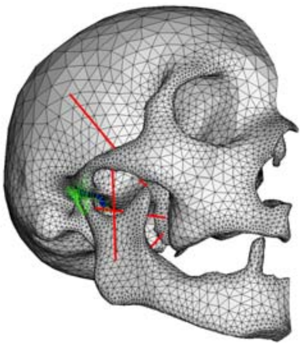

Figure 2: FE model of skull, mandible and the TMJ.

Ligaments and muscles represented by the connector elements were linked with 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. Distributing coupling constrains the motion of the coupling nodes to the translation and rotation of the reference node. This constraint controls the transmission of loads through weight factors at the coupling nodes. The constraint distributes loads, so that the resultant 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 Figure 2 and Figure 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 contact. 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 by the synovial fluid. Coefficient of friction was estimated to 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 16665.

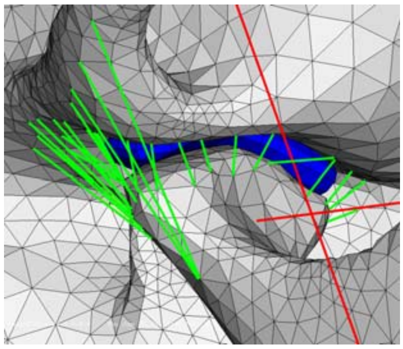

Figure 3: Detailed FE model of the TMJ; muscles (connector elements), ligaments (connector elements) and TM disc are shown.

Material properties: Data of the material properties of all TMJ parts were taken from published data. The cortical and cancellous bone of the skull and mandible were considered to be isotropic and linear elastic. Tooth and ligaments were also defined as isotropic and linear elastic. Because the range of magnitude of TM disc material properties in published data is large, Young's modulus and Poisson's ratio were estimated to values in Table 1. The TM disc was also defined as homogenous 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

Applied forces and boundary conditions: Advantage of using connector element was the possibility to apply

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resultant forces directly. Geometrical parameters are completely defined by the muscle insertion between the 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 side of the mandible. Magnitudes of all applied forces were taken from published data [2, 8].

Symmetry boundary conditions were applied on the sagital surfaces of the skull and mandible. The base of the skull was firmly constrained and tooth displacement in the z-direction was constrained for the normal jaw occlusion simulation. All applied forces are listed in Table 2.

Table 2: Muscle forces corresponding with normal jaw occlusion

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

Results

The results illustrate the stress distributions in the TMJ during a normal jaw occlusion. The stress distributions from this model are given in Figure 4 and Figure 5. High von-Misses stresses were seen at the mandible near the processus coronoideus. The maximum von Misses stress was about 5.5 [MPa].

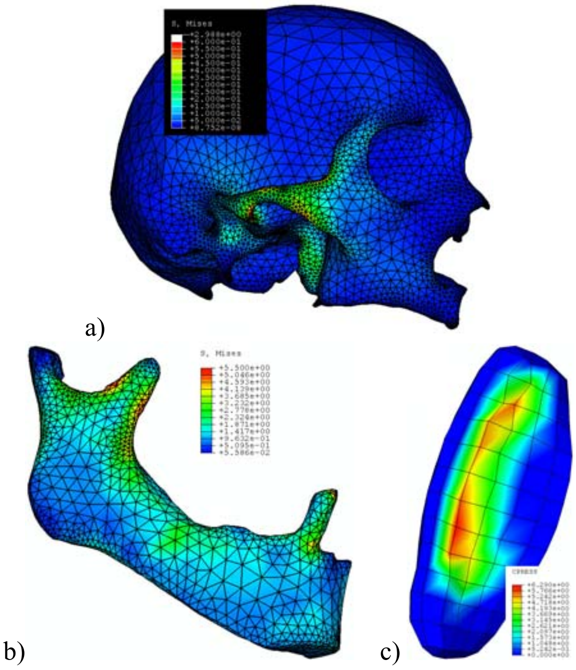

Figure 4: Distribution of the von Mises stresses [MPa] (a)in the skull, (b)in the mandible and (c)the distribution of the contact pressure [MPa] in the TM disc.

High contact pressures were seen at the contact surface on the TM disc, contact was defined between the TM disc and the mandible. The maximum contact pressure was about 6.3 [MPa].

Maximal von Misses stress on the skull were located on the arcus zygomaticus, where is connected m. masseter with the skull. The maximum von Misses stress was about 3 [MPa].

The forces in the ligaments were quite small. The maximum ligament forces were located in the joint capsule (0.3 N).

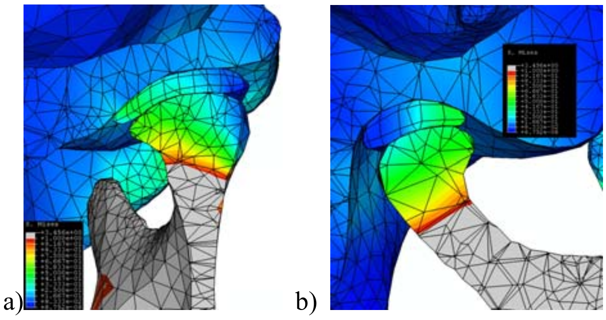

Figure 5: Von Mises stresses [MPa] in the temporomandibular joint - (a) the frontal plane (b) the sagital plane.

Discussion

The project describes a three-dimensional model of the temporomandibular joint. The presented model, as far as we know, is the first complete three-dimensional model. 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 as isotropic and linear in this analysis, so that it can provide preliminary results. In the next analysis, it is intend to broaden the information of the material behaviour and improve the final output.

Stress analyses in the joint components (disc, mandibular condyle and fossa eminence on the skull), all TMJ ligament and muscles have been analyzed associated with a normal jaw occlusion. It has verified the model for future studies and developments.

The TMJ kinematics is very sophisticated movement including shift and rotations in ordinary jaw closure. There are also several more complex movements that are performed by the TMJ joint such as shear. Location of the food plays also very important role during biting. Large stress distributions are usually on the opposite side than the food.

In the Laboratory of Biomechanics by CTU in Prague, the kinematics of TMJ is studied, so that the data could be also used for this FE model.

During the jaw opening the TM joint disc slides slightly and then it is drawn by muscle, so that it is not easy to describe it. 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

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complicated to set. Find the solution of the question will surely approach the TMJ model to the real joint.

Conclusions

The used model is suitable for modeling the physiological situation in the TMJ and it was verified with the normal jaw occlusion situation. The results of this analysis will be used for development a new total TMJ replacement. Material properties and loads could be verified experimentally and improve the model.

Acknowledgement

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