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Analyses of the Temporomandibular Disc

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Abstract: This project is the beginning of a large research work with a goal to develop a new total replacement of temporomandibular (TM) joint. First aim of this work was to determine the relative displacement of the TM disc and the mandible during mouth opening. The movement of the TM disc was studied using a magnetic resonance imaging. Sagittal static images in revolved sections of the TM joint were obtained in various positions of jaw opening from 0 to 50 mm. The results provided a description of the TM disc displacements as a function of jaw opening. The displacements of the mandible and TM disc were about 16 mm and 10 mm respectively at mouth opening of 50 mm, maximum rotation of the mandible was 34ş. The results of these measurements can be used for clinical diagnostics and also they were used as inputs for the follows finite element analysis (FEA). Second aim of this work was to create stress and strain analysis of TM joint using non-linear FEA. Complex of TM joint consists of mandibular disc, half skull and half mandible during normal jaw opening. The results illustrate the stress distributions in the TMJ during a normal jaw opening.

Introduction

Problem of face and jaw disorders is very extensive and complex, and it requires much effort to elaborate and implement new curative procedures and renew the function and shape of the orofacial area with respect to the patient. It is estimated that 20% of the population suffers from temporomandibular disorders (TMD). Several studies have reported disc perforations and degeneration of the articulating surfaces [1]. Any TM disc motion derangement during mouth opening will significantly influence TMD. From the anatomical and biomechanical point of view, the temporomandibular joint (TMJ) is a sophisticated bicondylar articulatory complex that places high demands 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 in the human body, which in conjunction with the individual uniqueness of this joint place high demands on its design and reliability. This project is the beginning of a large research work with the goal to develop a new total replacement of TMJ. Temporomandibular joint replacement is very sophisticated and with individual approach to patient. For successful development of the TMJ replacement it is very important to know several conditions. First of them is to understand and to know how to describe the relative motion of the system of TMJ parts. It is therefore necessary to perform experimental measurements in order to observe this physiological movement. Condylar and TM disc displacements are useful in understanding the aetiology of the disease and in evaluating the treatment. The movement of the TM disc during jaw opening and closure is very sophisticated. It was difficult to depict its motion exactly, because the disc shape changes significantly during the motion. The number of experimental studies is limited, because it is difficult to insert experimental devices, such as strain gauges, into the joint without causing damage to its tissues and influencing their mechanical behaviour. In several studies, condylar motion has been studied directly with the use of MRI [2, 3, 4], videoanalysis [5], or ultrasound imaging [6]. The data obtained from this experimental measurement during jaw opening was measured only for a maximum distance between central lower and upper incisors of 17 mm. In fact, the maximum comfortable mouth opening is greater (approx. 30–50 mm), and moreover, there were no references about TM disc displacement. Experimental and numerical studies concerning jaw movement and the distribution of the loads in the TMJ have been performed in many models [7, 8, 9, 10]. However, the TM disc is crucial for proper TMJ function, and it has been omitted or simplified in many numerical models and experiments [9, 11, 12]. Second necessary condition for successful development of the TMJ replacement is to know distribution of the loads in the TMJ. Mathematical models of the human masticatory system including the TMJ have been demonstrated to be a powerful tool to predict the loads acting on this joint [7, 8, 9, 10, 12, 13, 14, 15, 16]. However, many studies have oversimplified the geometry and behaviour of the TM disc. Therefore, the tissue deformations and the distribution of loads inside the joint could not be analyzed. Numerical modelling can provide with further of the understanding physiology of the joint but also pathogenesis of the joint diseases. Application of the finite element stress analysis technique to the biomechanical investigation of the TMJ is very suitable. Finite element analyses of TMJ were created by many authors [7, 10, 12, 13, 15], but in this analysis was used some simplification. Problems of all FE analyses are definition of the muscle forces, movement of the TM disc during jaw opening and definition of TM disc material properties. Some analyses were created as 2D contact problems or separated parts were analyzed. 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. Contacts interactions were defined between the TM disc and the skull and between the TM disc and the mandible.

Material and Methods

Kinematics of the TM disc

The experimental measurements were obtained on one volunteer (male, 25 years old) – only one TMJ with no abnormalities. Our measurement method is based on [2]. Imaging was carried out at the Radiodiagnostic clinic of the 1st Medical Faculty at Charles University. The measuring device was Intera 1.5 T (Philips), and the subject was scanned into 3 mm thick slices with the FFE dynamic scan sequence in the image plane of the slices. The head was fixed to avoid major displacements; smaller displacements such as swallowing and position discomfort of the head were corrected using the geometric transformation described below. The image plane was rotated from a mid-sagittal plane of 30ş in the direction of the jaw (Figure 1). Image plane sections of TMJ were scanned in the specified location of jaw opening from 0 to 50 mm (distance between central lower and upper incisors) using a customised 1-directional "spreader" device. We used a Vernier calliper design and proposed an appropriate shape for convenient mouth opening. Six static mouth opening positions were obtained, starting with the maximum jaw opening (50 mm) and proceeding to closure (0 mm), and an MR image of the TMJ was taken for each position. It was necessary to minimize the imaging time over which the patient must keep the jaw open. This can be uncomfortable for the patient in the supine position, as saliva collects in the back of the pharynx [3, 17].

The contours of the TMJ components: fossa mandibularis and tuberculum articulare on the skull, the mandible condyle and the TM disc were taken from the MR images. These contours were traced in one slice (our chosen image plane) by parametric curves defined by the number of points for each part of the joint. We assigned two points at each end of the curve; there were set points A, B and C, D on the skull and on the mandible condyle, respectively (Figure 2). One reference point (marker) was assigned for the fossa mandibularis – point E, and also for the mandibular condyle – point F (Figure 2). The positioning of the reference point was hard to define due to the broken shapes of the biological structures. We determined the points as intersection of normals (centre of curvature) on the above mentioned contours (points E and F related to skull and mandible, respectively, Figure 2). It was more difficult to decide how to deal with the disc reference points, because the TM disc changed its shape significantly during the motion. The only solution that we found was to define markers for each mouth opening in the location of the muscle and ligament conjunction, points G, H respectively, because these particular points could be explicitly defined.

The displacements for each part of the TMJ were obtained from the sequence of the contour transformation (trajectories of all points are shown in Figure 3). First, the transformation described the position of all reference points into the local coordinate system of the skull (index S). A global (index G) Cartesian coordinate system (CCS) was chosen to coincide with the coordinate system in the MR image

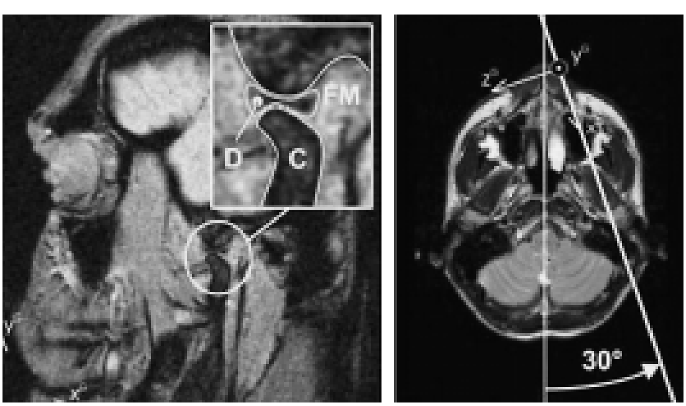

Figure 1 – MR image of the TMJ at the mid-opening of the mandible with initial point and defined CCS; image plane with the highlighted condyle – C, fossa mandibularis – FM and the TM disc – D (on the left), rotation of image plane from mid-sagittal plane (on the right).

(Figure 1). The first MR image (assigned as the *n*-th index) was established as a reference image. Second, all markers were transformed from the local coordinates (from the above-mentioned transformation) into the global coordinate system for all mouth opening positions; the temporal bone points A, B and E were identical for all positions. This was essential, because although the head was fixed, the skull might move towards the skin during the examination. The third was the transformation of point F into the coordinate system from the global CCS to the local CCS of the mandible (index M). Finally, point F (local CCS of the mandible) was translated and rotated into the global coordinate system for all mouth opening positions. The four transformations can be described by the following instructions [18]:

1. Coordinate transformation of reference points B, C, D, E, G and H from the global (upper index G) Cartesian coordinate system to local CCS of the skull (upper index S) respectively for *i=1, 2,.., n*, when *n* is position number of jaw opening (in our case *n=6*) and ***r*** indicates extended radius vector.

$$r^G_{Bi}, r^G_{Ci}, r^G_{Di}, r^G_{Ei}, r^G_{Gi}, r^G_{Hi} \rightarrow r^S_{Bi}, r^S_{Ci}, r^S_{Di}, r^S_{Ei}, r^S_{Gi}, r^S_{Hi}$$

2. Correction of points B, C, D, E, G and H position in global CCS respectively for *i=1, 2,..., n*, when *n* is the number of the jaw opening position.

$$r^S_{Bi}, r^S_{Ci}, r^S_{Di}, r^S_{Ei}, r^S_{Gi}, r^S_{Hi} \rightarrow r^G_{BNi}, r^G_{CNi}, r^G_{DNi}, r^G_{ENi}, r^G_{GNi}, r^G_{HNi}$$

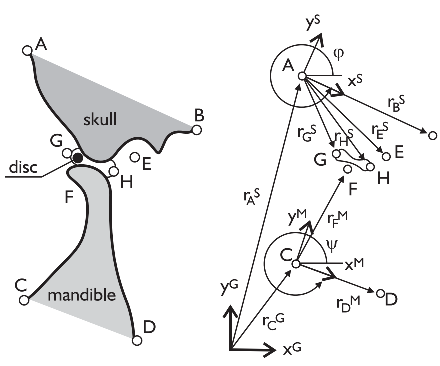

Figure 2 – Contours of TMJ part with assigned reference points from A to H for maximum mouth opening (on the left); defined coordinates systems, index G – global CCS, index S – local CCS of the skull and index M – local CCS of the mandible (on the right).

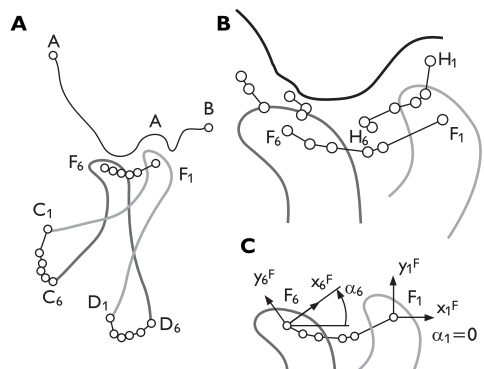

Figure 3 – Scheme of the reference point motion (index 1 mouth is closing, index 6 mouth is opened to the maximum): (a) scheme of the mandibular condyle movement, (b) image detail of the TM disc reference point movement, (c) coordinate system for graphic interpretation of the reference point motion.

3. Coordinate transformation of point F from global (index G) CCS to local CCS of mandible (index M)

$$r_{Fn} \xrightarrow{GM} r_{Fn}.$$

4. Computation of another position (*i=1, 2,..., n-1*) of jaw opening was done in global CCS.

FE analysis of the TM joint

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 simplification of the FE analysis. Geometrical model of the TMJ is shown in (Figure 4). Model of the TMJ was exported from the CAD program in to the automated mesh generator NETGEN, where were generated four-noded tetrahedral elements of the skull and mandible. TM disc was meshed by eight-noded brick elements in to the TrueGrid® mesh program. Finally muscles were defined by connector elements. This special element allows various definitions of the material properties, loading forces and the element behaviour. Connector element type axial was used for this application. This type provides a connection between two nodes where the relative displacement is along the line separating the two nodes.

It models 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, measures the change in distance separating the two nodes. Muscles represented by connector elements were linked with mandible and skull by distributed coupling constraints. This

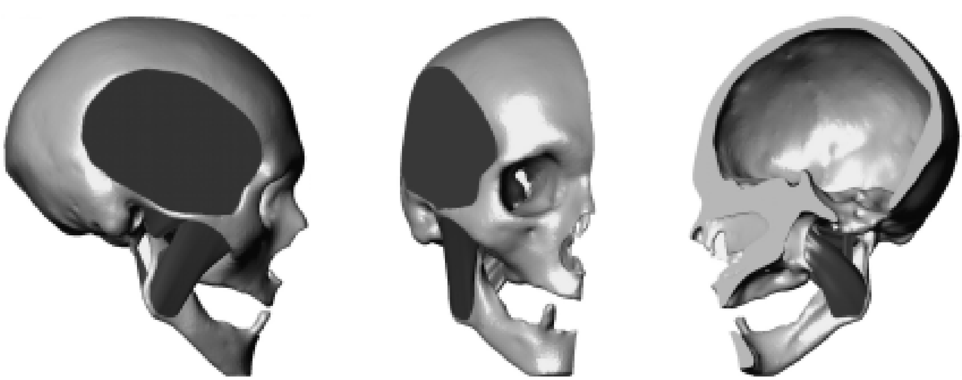

Figure 4 – Geometrical model of the skull and mandible. All muscles and ligaments are shown.

represented muscle insertion in to 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 is enforced in an average sense in a way that enables control of the transmission of loads through weight factors at the coupling nodes. The constraint distributes loads such that the resultants of the forces at the coupling nodes are equivalent to the forces and moments at the reference node. FE model of the TMJ is shown in (Figure 5).

FE analysis was defined as a nonlinear contact task and solved in ABAQUS 6.6 (Hibbit, Karlsson, Sorensen, Inc., Providence, RI). Contact interactions were defined between the TM disc and the skull and between the TM disc and the mandible. 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 existence of the synovial fluid. Coefficient of friction was estimated 0.08. The FE model consisted of 180 eight-noded elements, 54578 four-noded tetrahedral elements, and 48 connector elements. Total number of nodes was 16665. Data on the material properties of all TMJ parts were taken from published data. The 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 range of magnitude TM disc material properties in published data is big, Young's modulus and Poisson's ratio were estimated. TM disc was also defined as homogenous and isotropic. All material properties assigned to the structural elements are listed in (Table 1) [12, 19].

Advantage of using connector element was the possibilities apply resultant forces directly. Geometrical parameters are completely defined by the muscle insertion in the bone. Normal jaw clenching was used for this analysis and forces were applied in connector elements. All forces were assumed to be symmetrical and had equal

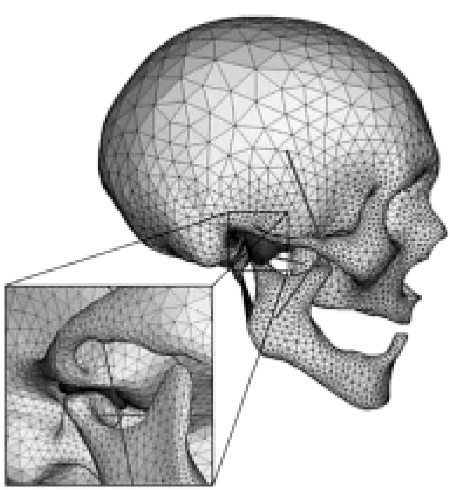

Figure 5 – FE model of skull and mandible. All muscles (red lines), all ligaments (green) and TM disc (blue) in detail were shown.

magnitude on the right and left side of the mandible. Magnitudes of all applied forces were taken from published data [3, 11, 20]. Symmetry boundary conditions were applied on the sagittal surfaces of the skull and mandible. Base of the skull was constrained and tooth displacement in the z-direction was constrained for normal jaw clenching

Results

Results of the experimental measurements showed the motion of the TM disc and the mandible markers during mouth opening. Figure 3 shows an example of the opening movement path of the reference points. We observed the relative motion of the TM disc and the mandible in the x-axis and in the y-axis and also the rotation depending on the mouth opening (Figure 6, Table 3). Regression of the measured points coordinates, depending on mouth opening, represents a third- or second-order polynomial curve (Figure 6). A correlation coefficients range from $R^2=0.97$ to $R^2=0.99$. The movement of the TM disc is shown in Fig. 6 and the reference points G, H displacements are described in Table 3. which show the TM disc behaviour during jaw opening. The motion of the mandibular condyle was

Table 1 – Material propertiesof the TMJ components

Material	Young's modulus [MPa]	Poisson's ratio [–]
Bone	16300	0.31
Ligaments	1200	0.28
Tooth	19000	0.30
TM Disc	16	0.45

Table 2 – Muscle forces corresponding with maximal jaw clenching muscles

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

Table 3 – Values of displacement of all reference points F, G, H in the specified directory and rotation of mandibular reference point F

m [mm]	α [°]	Mandible Point F [mm]		TM disc Point G [mm]		TM disc Point H [mm]	
		x	y	x	y	x	y
0	0	0	0	0	0	0	0
10	9.46	–6.01	–2.82	1.53	–1.31	–0.43	–3.45
20	14.75	–7.69	–3.33	1.20	–1.93	–1.40	–4.37
30	20.53	–11.26	–2.86	–2.80	–1.13	–3.55	–4.86
40	27.10	–13.51	–2.53	–4.17	0.66	–6.79	–6.38
50	34.39	–15.81	–1.10	–9.83	1.85	–6.03	–6.82

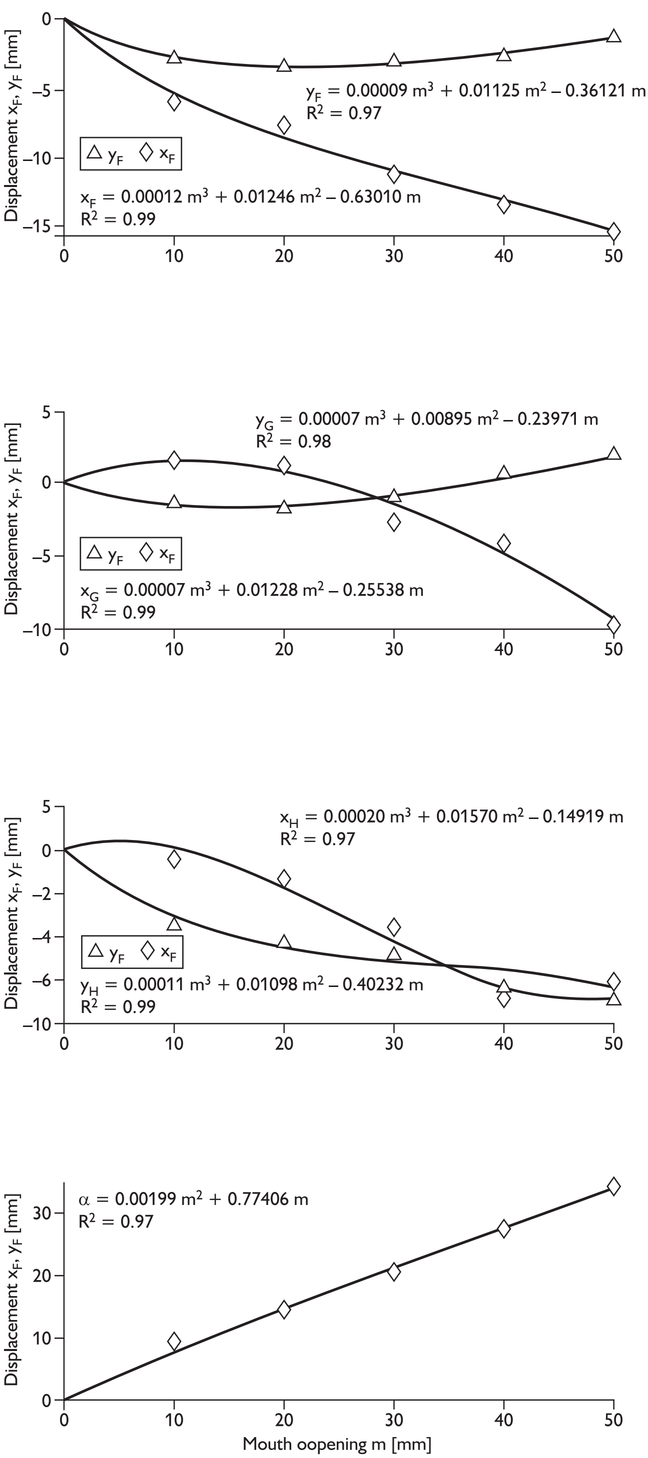

Figure 6 – Displacement of reference points on the TM disc and the mandibular condyle (from top): motion of mandible reference point F; relative motion of the TM disc reference points G and H; rotation of mandible about reference point F.

investigated in two directions and one angle. The initial position was established for a closed mouth, where the angle was considered as 0°, so that the displayed angle was absolute. Figure 6. and Table 3. show that the maximum displacement in the x-direction was 15.81 mm, and in the y-direction it was 3.33 mm. So the maximum translational displacement was 15.85 mm and the maximum rotation of the mandibular condyle was 34.39° (Figure 6, Table 3).

Results of the FE analysis illustrate the stress distributions in the TMJ during a normal jaw clenching. The stress distributions from this model are given in (Figure 7 and Figure 8). High von-Misses stresses were seen at the mandible near the processus coronoideus. The maximum von Misses stress was about 5.5 [MPa]. High contact pressures were seen at the contact surface on the TM disc, contact was defined between TM disc and 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).

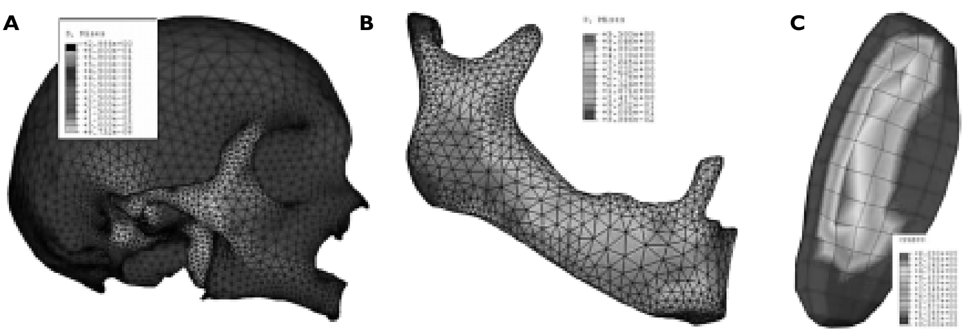

Figure 7 – Distribution of the von Misses stresses [MPa] in the skull (a) and mandible (b) and distribution of the contact pressures [MPa] in the TM disc (c).

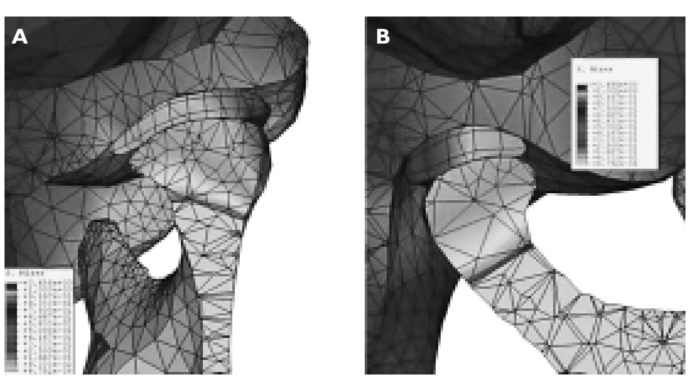

Figure 8 – Distribution of the von Misses stresses [MPa] in the temporomandibular joint. View of the frontal plane (a) and sagittal plane (b).

Discussion

The TM disc plays a crucial role in TMJ motion; it is therefore necessary to know its mechanical behaviour as well as its movement. The displacement of the mandibular condyle was described in previous publication [2] for maximum mouth opening of 17 mm. This is not the maximum comfortable mouth opening, so it was necessary to broaden these measurements. In addition, there was no investigation of TM disc movement. The results for mouth opening of 17 mm have been used for computing FEA [10], but the results of this analysis must be insufficient. Our measurement method is based on [2], but we obtained a more complex description of the mandible and especially of TM disc behaviour. From our study we obtained the displacement of the TM disc and of the mandible condyle in relation to mouth opening. The maximum mouth opening was 50 mm; this distance was defined between lower and upper incisors. This study shows that the condyle first moves down and forward (downward and anteriorly) and then rotates open. This motion is shown in Figure 6. MRI is a non-invasive method which can be used easily and efficiently for visualization of soft tissues. Adjusting the MRI device was crucial. There are many scanning techniques, but in most of them the disc is not easily observed. Next, there can be significant loss due to slice thickness. Several experiments with MR specialists led to a proper scanning sequence. Finally, the precision of the results is also limited by the quality of the MR images and by the accuracy of the contours of the TMJ part. All parts were shaped according to their anatomical geometry in cooperation with an experienced dentist. One of the main disadvantages was that the individual quasi-static images that were analyzed in this initial study did not capture everything that was truly seen when examining the TMJ in motion. In [2] the motion of the mandibular condyle was studied for the reference point defined on the condyle, which does not seem to be precise. In our approach, the centre of the curvature should be the more exact description of the reference point. Another disadvantage of the approach is that there were just two dimensions. Improvement into a three-dimensional scheme will surely be one of the first future developments. The spatial conception needs to be more accurate due to the extremely complex shape of the TM disc. A further disadvantage was that only one subject on one side of the joint was examined. A study is already in progress to overcome this disadvantage. We intend to supplement some statistical evaluation to enhance the statements presented here. The study provided 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 their anatomical geometry which was sampled with high resolution. This study verified applied model in the real situation during a normal jaw clenching. Stresses in the joint components (disc, mandible, skull and ligaments) with a normal jaw clenching have been analyzed. Results of this analysis shown, that the numerical simulation of this geometrically complicated joint is possible by the FEM. Compared with the results taken from published data [7, 8, 13], the stress distribution in the

TM disc are corresponding. In this model simple material definitions were used, but this pilot study was made for model verification. Next simplification was ligaments simulation by the connector elements. Finally the model didn't include deformable cartilage layers on the articulating surfaces of mandible and skull. All of these simplifications will be changed in the next generation of the TMJ model.

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