

Finite element analysis of stresses in the maxillary and mandibular dental arches and TMJ articular discs during clenching into maximum intercuspation, anterior and unilateral posterior occlusion

Gaivile Pileickiene, Algimantas Surna, Rimantas Barauskas, Rimas Surna, Algidas Basevicius

SUMMARY

The objective of this study was to investigate distribution of stresses in the human TMJ discs, generated during clenching into various occlusal positions.

The work presents a biomechanical finite element model of interaction of mandibular and maxillary dental arches and the TMJ discs of a particular person, based on real geometrical data obtained from spiral computed tomography two-dimensional images. 3D contour coordinates - point clouds were collected from these images and solid model was created. The system under investigation consisted of eight basic parts: two rigid structures representing the mandibular and maxillary dental arches, two mandibular condyles, two mandibular fossae of temporal bone, and solid models of two articular discs. The model of maxillary dental arch was fixed in space. The model of the mandibular dental arch was able to move in space synchronically with the mandibular condyles under action of applied forces, which were considered as prescribed and known at insertion points of masticatory muscles. The motion of the mandible was constrained by interdental contact interactions and contact interaction with articular discs, which were situated in between mandibular condyles and mandibular fossae of temporal bone. The model was implemented by using LS-DYNA finite element software.

The obtained results presented a 3D view of stresses exhibited in the articular discs, as well as the real contact points of dental interactions at given masticatory geometry of a particular subject and the values of interaction forces. The expected practical value of the developed model is the facilitation of biomechanical evaluations of the influence of tolerances of teeth shapes and occlusal areas together with the supporting areas on the final stress distribution in the dental arches and articular discs.

Key words: biomechanics, mathematical model, finite element stress analysis, temporomandibular joint disc.

INTRODUCTION

The biomechanical functions of teeth generally result in stresses, which are transferred from the teeth through the periodontal ligaments, mandible, maxilla and temporomandibular joints and produce strains and stresses in all of them. Understanding the nature of strain and stress distribution is essential for better diagnosis and

treatment of stomatognathic diseases and reconstruction of masticatory function. Unfortunately, the stresses can not be measured directly in a non-destructive way. The number of direct studies on the masticatory system is limited, because its structures are difficult to reach and the applications of experimental devices, such as strain gauges, inside the structure introduce damage to its tissues, which interfere with normal function and influence their mechanical behavior. Dental biomechanics is an interdisciplinary approach in which engineering principles are applied to dentistry [1] (Asundi, 2000). During the latter decades numerical methods and in particular the finite element method became a powerful analysis instrument of structural behavior and interaction analysis of bodies, systems and environments of a very different physical nature. In principle, most of the real physical can be more or less adequately represented and modeled by using appropriate computational software. Still persisting

¹Clinic of Prosthodontics, Kaunas Medical University, Lithuania

²Kaunas University of Technology, Lithuania

³Radiology Clinic, Kaunas Medical University, Lithuania

*Gaivile Pileickiene*¹ – D.D.S., assist. prof.

*Algimantas Surna*¹ – D.D.S., PhD, assoc. prof., Head of Clinic of Prosthodontics

*Rimantas Barauskas*² – Dr. habil., prof., Head of System Analysis Department

*Rimas Surna*² – PhD, assoc. prof.

*Algidas Basevicius*³ – MD, PhD, prof., Head of Radiology Clinic, Kaunas Medical University, Lithuania

Address correspondence to *Gaivile Pileickiene*, Clinic of Prosthodontics, Sukileliu 51, Kaunas, Lithuania.
E-mail: gaivile@gmail.com.

simulation difficulties in biomechanics are related mainly with the material models of investigated objects. They are always empirically determined, and often present quite complex constitutive relations. A characteristic feature of jaw and teeth interaction biomechanics is complex geometry of contacting surfaces. Finite elements programs employing the explicit dynamics approach are most successfully used for simulation of such systems. In this work we employed LSDYNA finite element software [2, 3]. Explicit dynamics programs simulate the processes in time or in pseudo-time by extrapolating the condition of the system at the next time step on the base of the state of the system at current time step and taking into account forces acting on the system. As calculations are performed step-by-step, complex contact interactions are robustly managed and interaction forces determined. Generally, numerical simulation of physical systems and processes presents a lot of interesting information about their condition and behavior, which cannot be observed or measured directly. Often it can be used instead of making experiments on real physical systems. It considerably reduces the price of the experiment. However, a certain amount of experience and attention is necessary in order to obtain the simulation data that can be trusted as being close to reality. On the other hand, in process of simulation a lot of “non-quantified” understanding about real physical behavior of the analyzed system is obtained. In this way, it can indirectly suggest the way to find the improved practical solutions. A remarkable advantage of the finite element method is the chance to study areas that are difficult or impossible to access without any risks to a living subject of investigation [4] (Jeon, 2001). The use of finite element method allows studying a single tooth, a set of teeth, or even the relationship between maxillary and mandibular dental arches on a more solid and precise biomechanical basis than other methods such as photoelastic models and strain gauges [5] (Daegling, 2000). Therefore, with this methodology it is possible to have quantitative and qualitative representations of dental and mandibular biomechanics to evaluate displacements, strains and stresses, which may occur in biomechanical structures.

The aims of this study were:

- 1) to create a biomechanical three-dimensional model of mandibular and maxillary dental arches and the TMJ discs of a particular person;
- 2) to verify the models ability for finite element analysis of stresses, generated in the temporomandibular discs during clenching.

MATERIALS AND METHODS

Skeletal morphology

Object of research was one cadaver of 20 year old man. The research protocol of this study was approved by Committee of Bioethics (Kaunas University of Medicine). Computer tomography scanning (CTS) was used to obtain two-dimensional images necessary for

creating 3D geometrical models. Multisection spiral computed tomography (General Electric) was performed in the area from infraorbital region to the base of mandible and 1500 slices within thickness of 0.625 mm were gained. Case-oriented software was created to extract morphological information of surfaces for each component of the biomechanical system independently. 3D contour coordinates (point clouds) were collected from the images and solid models were created. Three-dimensional geometrical models of all components comprising the biomechanical system were created using the “Image Pro – Plus” software (Media Cybernetics, USA). Receiving of skeletal morphology and 3D geometry reconstruction was described, in detail, previously [6] (Pileickiene et al, 2007).

The architecture of the model

The geometry of parts comprising the model as mandible, mandibular and maxillary dental arches, mandibular condyles and mandibular fossae of temporal bone have been obtained from spiral computed tomography two-dimensional images. By means of surfaces triangulation parts comprising the biomechanical system have been created: mandibular dental arch, maxillary dental arch, right and left mandibular condyles and mandibular fossae of temporal bone. The finite element mesh of parts comprising the model is presented in Fig. 1 (parts 1 to 4). The precision of computations will not change if the computational model includes only segments of rigid osseous structures, geometry of which is to be taken into account directly when modeling the contact interaction, Fig. 2. The method of spiral computed tomography allows to obtain a very precise reconstruction of 3D view of scanned parts and to produce a highly refined finite element mesh. However, in this work we chose a modest refinement of the parts, containing ~13000 nodes and ~18500 elements. The reasonable level of refinement of the model enabled to save computational resources, simultaneously preserving all important geometrical properties of the investigated biomechanical structure. The models of mandibular and maxillary dental arches were assumed to be rigid and therefore could be presented by means of shell structures. The number of nodes and elements necessary to present a shell structure is many times less than of a corresponding 3D solid body, and contributes to model size reduction. The value of penalty stiffness coefficient employed in the mathematical contact model of interdental contact interaction enabled to imitate the mobility of teeth comprising the dental arches.

The model of maxillary dental arch was fixed in space. The model of the mandibular dental arch was able to move in space synchronically with the mandibular condyles under action of applied forces, which were considered as prescribed and known at points of attachment of masticatory muscles. Clenching was simulated by the action of resultant force vectors of four bilateral masticatory muscles, responsible for the elevation of the mandible (masseter, temporalis, lateral

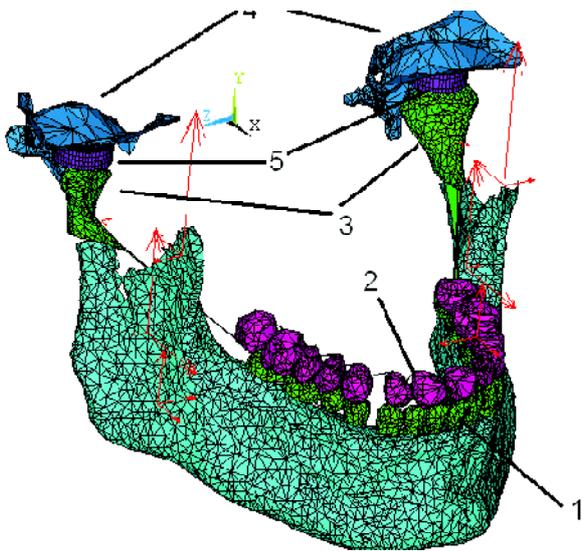


Fig. 1. The finite element meshes of parts comprising the model - full geometry: mandibular (1) and maxillary (2) dental arches, mandibular condyles (3), mandibular fossae of temporal bone (4) and solid models of articular discs (5)

and medial pterygoid muscles), which was assumed as static occlusal load [7] (Korioth, 1997). Simulated occlusal forces were applied at the model nodes representing the areas of anatomical insertion of four masticatory muscles, Fig. 3. Maximum muscle forces, related with their physiological cross-sectional areas, were defined as shown in Table 1 [8] (Koolstra, 1992). Clenching movements were simulated by a simultaneous activation of the four muscles, with 25% output of maximum muscle force. The forces comprised a total of 262 N, which has been described as a moderate physiological masticatory force [9] (Shinogaya, 2001). Different 3D views of the applied force system can be examined in Fig. 4. The actual points of application of muscles forces have been presented as extra nodes

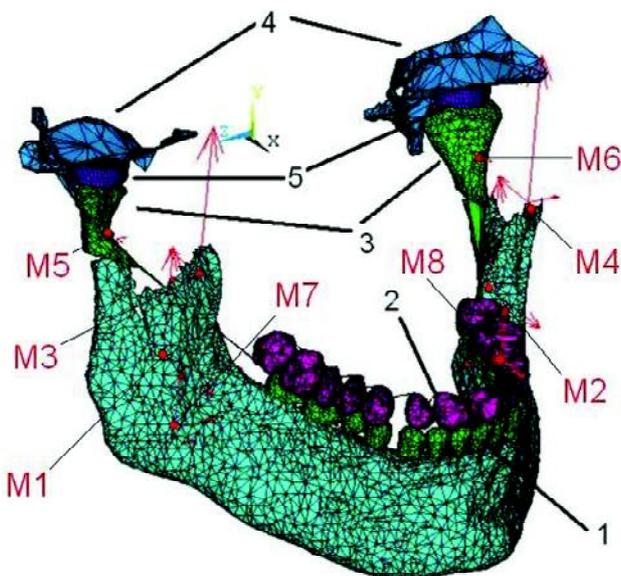


Fig. 3. Insertions points of masticatory muscles (M1, M2 – m. masseter; M3, M4 – m. temporalis; M5, M6 – m. pterygoideus lateralis; M7, M8 – m. pterygoideus medialis)

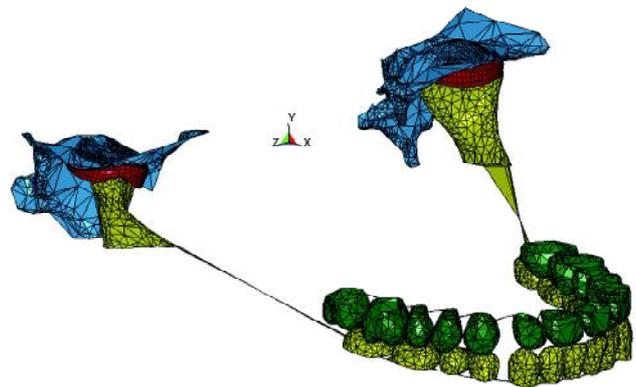


Fig. 2. The finite element meshes of the fragments of rigid parts used in computations

constrained rigidly to mandibular dental arch and performing the rigid body motion together with the mandibular dental arch. In Fig.1 the origins of red arrow triplets indicate positions of extra nodes used for force application, and the lengths of the arrows represent relative magnitudes of the components of the masticatory muscles forces.

The motion of the mandible was constrained by interdental contact interactions and contact interactions with articular discs, which are situated in between mandibular condyles and mandibular fossae of temporal bone, Fig. 1. The calculations were performed in three occlusal positions without the temporomandibular joint disc displacement. Structurally articular discs are fibrocartilaginous tissue so their geometric shape could not be scanned by means of computed tomography. Therefore we generated the geometry of articular discs mathematically by using a mathematical “material forming” procedure. The final result of the process is presented in Fig. 5, where the deformed articular disc fills in the space between condyles and fossae. The obtained geometrical shape of the articular disc is assumed to be as initial one for subsequent calculations. Therefore the residual stresses generated during articular “disc forming” process are set up to zero again. Biological form of the articular disc’s perimeter is not relevant to the experimental analysis of stresses because in the physiological clenching conditions articular discs are “fixated” onto mandibular condyles. To describe mechanical behavior of the structure, knowledge of the value of two parameters is sufficient: Young’s elastic modulus (rigidity) and Poisson’s ratio [10] (Boschian, 2006). Different reference sources [11, 12] (Koolstra, 2005; Hirose, 2006) agree that articular discs in occlusion

Table 1. Physiological cross-sections and maximum forces of the masticatory muscles

Masticatory muscle	Physiological cross-section, cm ²	Maximum Muscle force, N
Masseter muscle	8.0	376.0
Temporalis muscle	9.1	427.7
Lateral pterygoid muscle	0.8	37.3
Medial pterygoid muscle	4.4	207.6

Data from Koolstra et al [8].

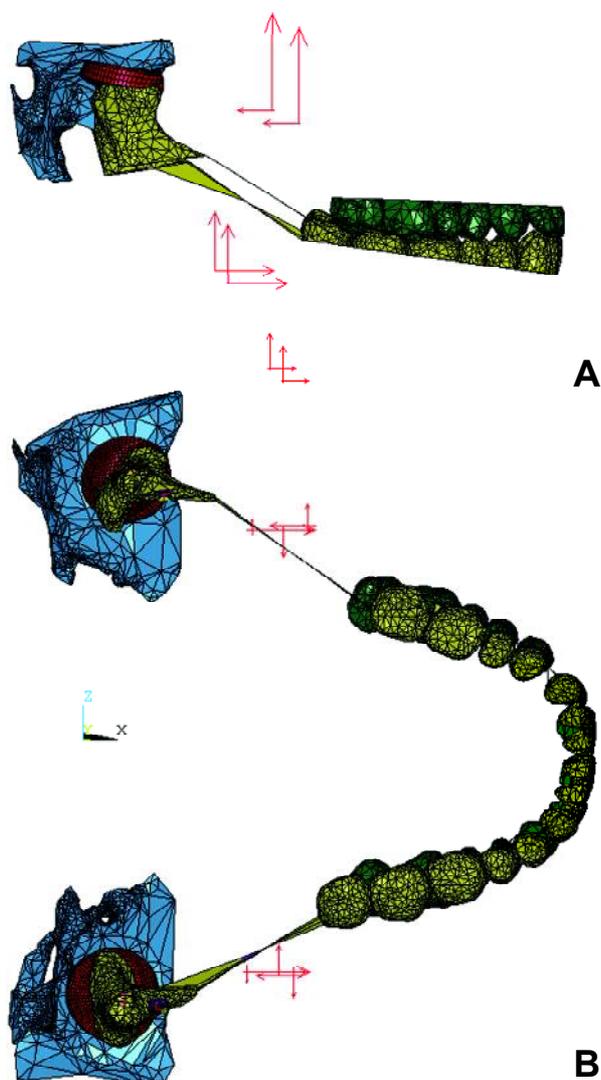


Fig. 4. The force system applied at extra nodes, which represent the points of attachment of masticatory muscles: A – side view and B – bottom view

simulation can be modeled as elastic isotropic solids. Non-linear elasticity model with Young's modulus 30.9-41.4 MPa up to stress level of 1.5 MPa, and Young's modulus 92.4 MPa above stress level 1.5 MPa has been employed. Poisson's ratio 0.4 of the material has been used. The values of mechanical characteristics used in our study were estimated from compressive stress-relaxation tests using experimental animals and previously reported by Tanaka et al. [13] (Tanaka, 1999) (Table 2).

The system under investigation consisted of eight basic parts: two rigid structures representing the mandibular and maxillary dental arches, two mandibular condyles, two mandibular fossae of temporal bone, and solid models of two articular discs. The final view of computational model with applied muscle force system and mathematically generated articular discs, ready for numerical experiments is presented in Fig. 6. To verify our model's ability for finite element analysis of stresses, generated in the temporomandibular discs during clenching, we simulated various clenching conditions: clenching into maximum

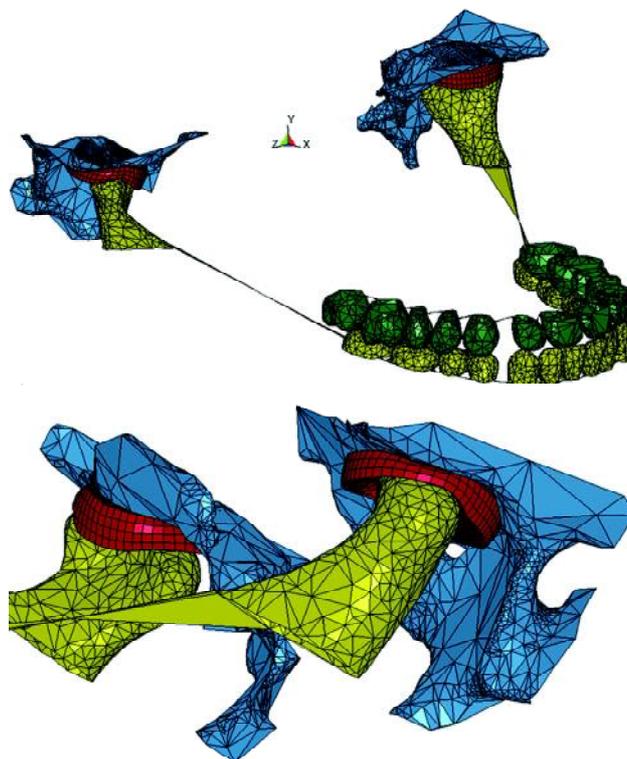


Fig. 5. Mathematically generated geometrical shapes of the articular discs in between of mandibular condyles and mandibular fossae of temporal bone

intercuspatation, biting with four frontal teeth and clenching with unilateral (left side) four posterior teeth.

RESULTS

Numerical experiment No. 1

Simulation of clenching into maximum intercuspatation – contact between all the teeth in the maxillary and mandibular dental arches.

Rigid body to rigid body contact between dental arches has been investigated under action of applied force system at extra nodes as in Fig. 6. The sliding contact with friction coefficient 0.2 has been assumed in condyle-articular disc and fossae-articular disc contact pairs. Distribution of stresses (von Mises) in the temporomandibular joint discs in the full-arch clenching condition is presented in Fig. 7, A-C. The von Mises stress is a mathematical combination of all components of both axial and shear stresses. It is commonly used to represent the total stress a given region is experiencing [14] (DeVocht JW). Fig. 7, A presents axonometric view of the system. Fig. 7, B presents the contour plots of von-Mises stresses in articular discs, where the articular fossae have been removed for visualization needs. Fig. 7, C presents the contour plots of von-Mises stresses in articular discs, where the condyles have been removed for visualization needs. It is obvious that stress distribution in both articular discs for this particular person in the condition of full-arch clenching is slightly asymmetric. The largest stresses were located in the central part of articular discs, directly contacting with the mandibular condyles,

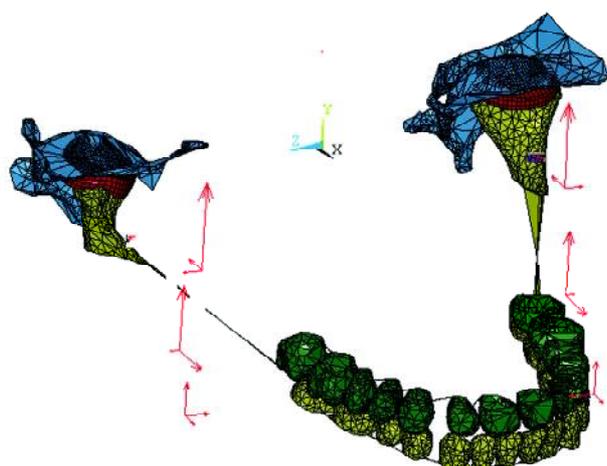


Fig. 6. The final computational model

their maximal values were 4.86 MPa. During the experiment articular discs were in the central position, typical of the maximum intercuspation.

Numerical experiment No. 2

Simulation of anterior occlusion – biting with four anterior teeth of the maxillary and mandibular dental arches.

Contact of only four frontal teeth was implemented by positioning a thin occlusion plate (Young's modulus ~1000 Mpa, yield stress 22 MPa) in-between frontal parts of mandibular and maxillary dental arches, Fig. 8, A. Fig. 8, B-C demonstrate the contour plots of von Mises stresses in articular discs, where the articular fossae have been removed for visualization needs. It is evident that maximum stresses concentrated in the occlusion plate situated between the frontal teeth. The stress distribution in the articular discs in condition of frontal teeth clenching was slightly asymmetric, while the values of stresses were approximately 30% lower (3.29 MPa) in comparison with full – arch clenching condition (4.86 MPa). During this part of experiment articular discs stayed in the central position because biting with four anterior teeth was simulated by placing a thin occlusal plate between the anterior teeth without protrusive movement of the mandible.

Numerical experiment No. 3

Simulation of unilateral posterior occlusion – clenching with four posterior teeth of the left side. Contact of only four left side posterior teeth was implemented by positioning a thin occlusion plate (Young's modulus ~1000 Mpa, yield stress 22 MPa) in-between left distal parts of mandibular and maxillary dental arches, Fig. 9, A. Fig. 9, B-C demonstrate the contour plots of von Mises stresses in articular discs, where the articu-

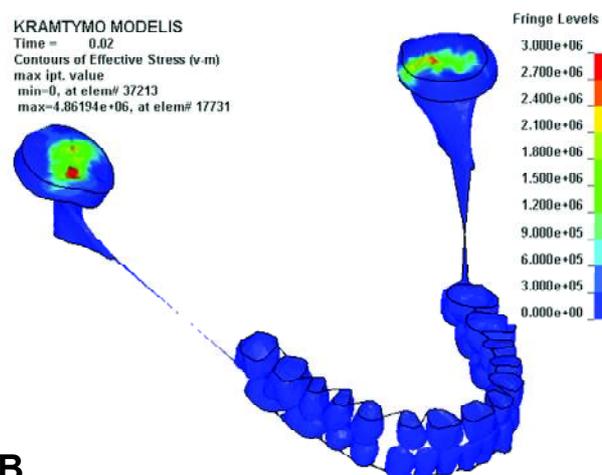
Table 2. Material properties of articular disc

Material	Elastic modulus, E (MPa)	Poisson ratio
Articular disc	30.9	0.4

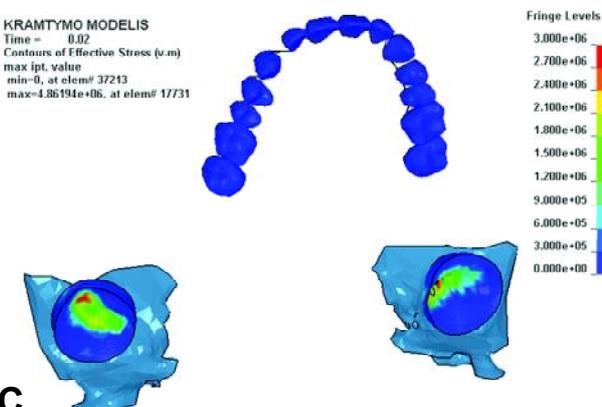
Data from Tanaka et al [13].



A



B



C

Fig. 7. Distribution of von-Mises stresses in the TMJ discs in full-arch clenching condition

lar fossae have been removed for visualization needs. It is obvious that maximum stresses are concentrated in the occlusion plate placed between the left side posterior teeth. The left articular disc was free of stresses, and moderate stresses (1.59 MPa) were generated in the right articular disc, which comprised 33% of the strength of stresses, generated in the articular disc during clenching into maximum intercuspation. During the last part of experiment articular discs were located in the central position because biting with four posterior teeth was simulated by placing a thin occlusal plate between the corresponding teeth without laterotrusive movement of the mandible.

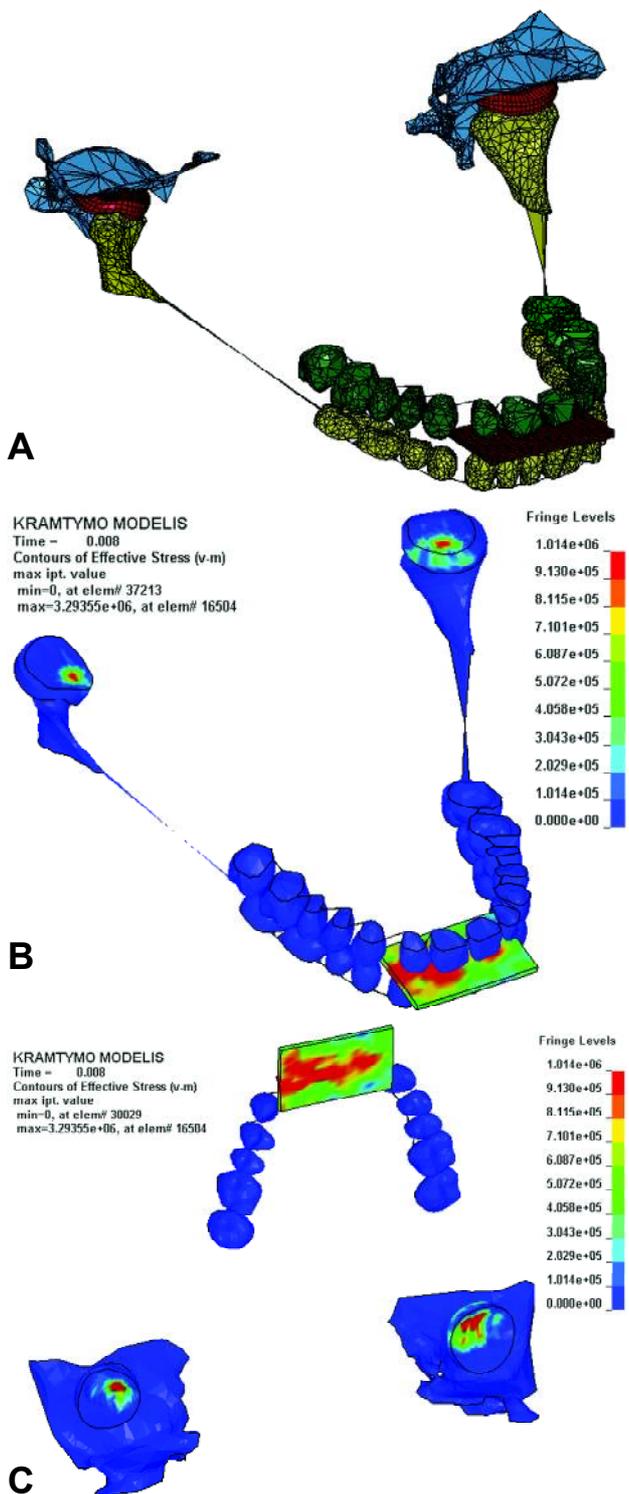


Fig. 8. Distribution of von-Mises stresses in the TMJ discs in four anterior teeth clenching condition

DISCUSSION

Finite element models have their current origin and real use in mechanical engineering analysis and design. Biological applications have been successful where mechanical principles would be of the most interest; for example in modeling human joints (hip, knee, etc.) [15] (Liau, 2001). In dentistry, models have been used to

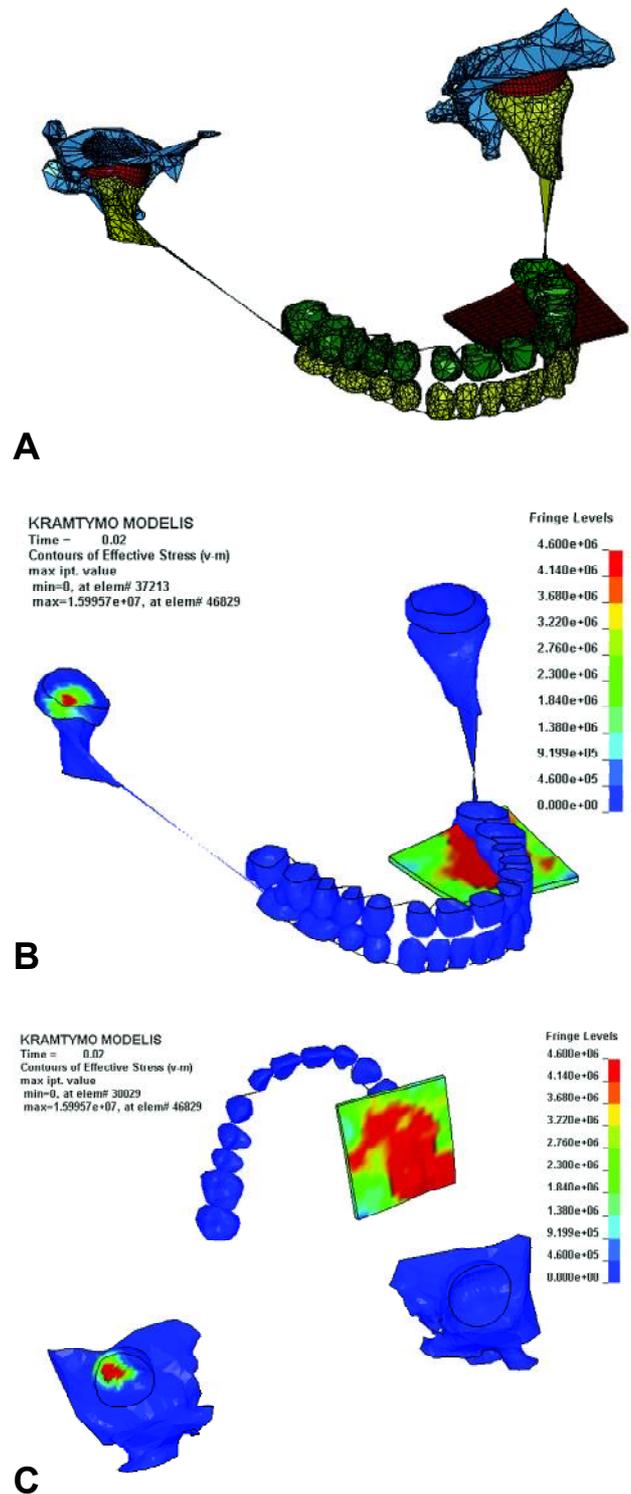


Fig. 9. Distribution of von-Mises stresses in the TMJ discs in unilateral (left side) four posterior teeth clenching condition

determine the stresses in different biologic structures, such as jaws, facial skeleton, dentition, periodontal ligament, temporomandibular joint [16, 17, 18, 19] (Cattaneo, 2003; Gross, 2001; Gomes de Oliveira, 2006; Toms, 2003; Hirose, 2006) and different dental restorative materials, for example, implants, composites etc. [20, 10] (Akpınar, 2000; Boschian, 2006). Most of the surveyed FEM studies analyzed the biomechanical behavior of individual

structures or materials, while we have tried to investigate interactions of stresses in the biomechanical system, representing the main elements of human masticatory system. Obviously, biomechanical models of the human masticatory system are not perfect, while they are based on a number of assumptions and simplifications [12] (Hirose, 2006). The adequacy of the FE computational model to the real system depends on the correctness of representation of the geometry and material properties of the modeled object, the type and number of elements and the boundary conditions imposed on the model [7] (Korioth, 1997). General point is that the precision of finite element calculations increases as highly refined meshes of the model parts are used. On the other hand, it is well known that highly refined meshes are necessary only at zones where high stress gradients are expected and at zones of complex and highly curved geometrical shapes of the model. In other words, the adaptation of the computational mesh density to the particular problem is always a good practice since it enables to achieve satisfactory accuracy and adequacy of the results by using reasonable model dimensions. The error estimation of the results of nonlinear problems solutions does always present a challenge, however, an „engineering“ way of checking the convergence of the solution can always be employed. This means a satisfactory coincidence of the simulation results obtained by using two different mesh densities the linear dimension of the elements of which differ approximately two times.

In order to obtain the correct representation of the geometry of the model we have chosen the minimal (0.625 mm) slice thickness possible to be registered by the CT device. This increased X-ray radiation for the object and made the research impossible to perform on the living person. In the future work the X-ray radiation could be reduced by scanning only the main parts of the masticatory system with high accuracy and after their geometry reconstruction integrating them into biomechanical system template, created from low accuracy (requiring low radiation) computed scanning images. Magnetic resonance imaging (MRI) could be used to get information about TMJ structures without introducing radiation to the patient, but this method is more applicable for evaluating the soft structures of TMJ, especially the articular discs [21] (Kobs, 2004), while our study was focused on the hard tissues of masticatory system, such as jaws and teeth. In reality the components of the biomechanical system are made of different materials, which are described in terms of their individual mechanical characteristics. In order to simplify the computations we assumed the models of mandibular and maxillary dental arches as rigid and whole, not accentuating single teeth and their periodontal ligaments. The simplification was performed because the main goal of this preliminary study was to evaluate the final stress distributions in the temporomandibular joint discs in the clenching condition. Appropriate extensions of the model would enable to investigate distribution of stresses and strains in all parts and in-between of them. The mechanical material properties of the articular disc were

obtained from the canine disc [13] (Tanaka, 1999), because no reliable material parameters for human are available in the literature. The positions of the points, the directions and magnitudes of forces exhibited by muscles were based on the values presented in reference literature [7, 8, 9] (Korioth, 1997; Koolstra, 1992; Shinogaya, 2001). As based on a previous studies [8] (Koolstra, 1992), a 25% activation of the masticatory muscles during clenching was used for the stress analysis, although large inter-individual and intra-individual differences in masticatory muscle activity may exist for the same task [12] (Hirose, 2006). Furthermore, the simultaneous activation of four different muscles at the same relative percentage of maximum muscle force was not real; for instance, there was estimated that electromyogram activities of lateral pterygoid muscle, anterior temporalis, and masseter muscles were dependent on the velocity [22] (Huang, 2005) and the phase of the closing jaw movement [23] (Soboleva, 2005). Besides, movements of the mandible are influenced not only by active muscle tensions generated by contracting muscle fibers, but also by multiple passive forces [24] (Pileickiene, 2004). However, even with the above-mentioned limitations, our model was able to demonstrate what effect clenching in different conditions had on the stress distribution in the temporomandibular joint discs. The distribution of stresses in the models of right and left TMJ articular discs of this particular cadaver during full-arch clenching into maximal intercuspation was slightly asymmetric; this could be appreciated as analogous with stress distribution during clenching in physiologic conditions. During simulation of anterior biting or unilateral posterior clenching the maximum stresses concentration was found in the occlusion plate, while the articular discs sustained only moderate stresses. Such distribution of stresses is appropriate for the normal masticatory function with well balanced occlusion, where the major part of occlusal load is directed to the dental arches and absorbed in the supporting tissues, while the temporomandibular joints receive only minor part of the load. Comparison of the results from this study to previous reports [12, 25, 26, 27] (Hirose, 2006; Chen, 1998; Radu, 2004; Naeije, 2003) was difficult because the applied load, material properties of the articular disc, boundary conditions and constraints at the articulating surfaces varied among these models. However, the stress distributions in our study were similar to the previous reports [26, 27] (Radu, 2004; Naeije, 2003) and the stress levels from our model were within the range of reported stress magnitudes. Previous studies [12, 25] (Hirose, 2006; Chen, 1998) reported that the maximum von Mises stresses in the disc were 0,85 to 8,0 MPa as compared to 4,86 MPa in the present study. Furthermore, previous reports were based on the partial models of temporomandibular joints, while our model included all the main elements of masticatory system. Whereas we have reconstructed higher accuracy three-dimensional geometry of all the parts, comprising masticatory system, appropriate extensions of the model would enable to investigate distribution of stresses and strains in all parts and interaction between them in different simulated

situations, such as disturbed occlusal equilibrium or alveolar bone loss due to the periodontal disease. In the future work the model could be supplemented with different prosthetic devices, such as periodontal splints or dental implants to simulate prosthetic treatment and predict its efficiency.

CONCLUSIONS

1. A computer-based three-dimensional finite element model consisting of the mandibular and maxillary dental arches, mandibular condyles and mandibular fossae of temporal bone, and two articular discs was created.

2. This initial FEM model has demonstrated that the computational modeling approach can be successfully used in the biomechanical study of stresses distribution in the constituent parts of the masticatory system.

3. The model can be conveniently extended in order to present the teeth mobility. This will cause the size of

the model to increase substantially because of the necessity of component models of every particular tooth in the dental arch, inclusion of periodontal ligament, improved representation of masticatory muscles activity etc.

4. The expected practical value of the developed model is the facilitation of biomechanical evaluations of the influence of tolerances of teeth shapes and occlusal areas together with the supporting areas on the final stress distribution in the dental arches and articular discs.

5. Future development of this model will enable the inclusion of differential material properties and simulation of the teeth, implants and prostheses in various pathological situations with the objective of creating prosthetic treatment predictive models, for example, occlusal equilibration or splint therapy for dental arches, affected by periodontitis.

6. Much more work is to be done in order to validate the created models on the base of physical experiments.

REFERENCES

- Asundi A, Kishen A. A strain gauge and photoelastic analysis of in vivo strain and in vitro stress distribution in human dental supporting structures. *Arch Oral Biol* 2000;45:543-50.
- LS-DYNA Keyword Users Manual. Version 960, vol.1, 2. Livermore Software Technology Corporation; March 2001.
- LS-DYNA Theoretical Manual. Livermore Software Technology Corporation; May 1998.
- Jeon PD, Turley PK, Ting K. Three-dimensional finite element analysis of stress in the periodontal ligament of the maxillary first molar with simulated bone loss. *Am J Orthod Dentofacial Orthop* 2001;119:498-504.
- Daegling DJ, Hylander WL. Experimental observation, theoretical models, and biomechanical inference in the study of mandibular form. *Am J Phys Anthropol* 2000;112:541-51.
- Pileickiene G, Varpiotas E, Surna R, Surna A. A three-dimensional model of the human masticatory system, including the mandible, the dentition and the temporomandibular joints. *Stomatologija. Baltic Dent Maxillofac J* 2007; 9:27-32.
- Korioth TWP, Versluis A. Modeling the mechanical behavior of the jaws and their related structures by finite element (FE) analysis. *Crit Rev Oral Biol Med* 1997;8:90-104.
- Koolstra JH, Van Eijden TMGJ. Application and validation of a three-dimensional mathematical model of the human masticatory system in vivo. *J Biomech* 1992; 25:175-87.
- Shinogaya T, Bakke M, Thomsen CE, Vilman A, Sodeyama A, Matsumoto M. Effects of ethnicity, gender and age on clenching force and load distribution. *Clin Oral Invest* 2001;5:63-8.
- Boschian PL, Guidotti S, Pietrabissa R, Gagliani M. Stress distribution in a post-restored tooth using the three-dimensional finite element method. *J Oral Rehabil* 2006;33:690-7.
- Koolstra JH, Van Eijden TMGJ. Combined finite-element and rigid-body analysis of human jaw joint dynamics. *J Biomech* 2005;38:2431-9.
- Hirose M, Tanaka E, Tanaka M, Fujita R, Kuroda Y, Yamano E, et al. Three-dimensional finite-element model of the human temporomandibular joint disc during prolonged clenching. *Eur J Oral Sci* 2006; 114:441-8.
- Tanaka E, Tanaka M, Miyawaki Y, Tanne K. Viscoelastic properties of canine temporomandibular joint disc in compressive load-relaxation. *Arch Oral Biol* 1999;44:1021-6.
- DeVocht JW, Goel VK, Zeitler DL, Lew D, Hoffman EA. Development of a Finite Element Model to Simulate and Study the Biomechanics of the Temporomandibular Joint. Available from: URL:http://www.nlm.nih.gov/research/visible/vhp_conf/devocht/vhpaper.htm.
- Liau JJ, Cheng CK, Huang CH, Lo WH. The effect of malalignment on stresses in polyethylene component of total knee prostheses – a finite element analysis. *Clin Biomech* 2002;17:140-6.
- Cattaneo PM, Dalstra M, Melsen B. The transfer of occlusal forces through the maxillary molars: A finite element study. *Am J Orthod Dentofacial Orthop* 2003; 123:367-73.
- Gross MD, Arbel G, Hershkovitz I. Three-dimensional finite element analysis of the facial skeleton on simulated occlusal loading. *J Oral Rehabil* 2001;28:684-94.
- Gomes de Oliveira S, Seraidarian PI, Landre J, Oliveira DD, Cavalcanti BN. Tooth displacement due to occlusal contacts: a three-dimensional finite element study. *J Oral Rehabil* 2006;33:874-80.
- Toms SR, Eberhard AW. A nonlinear finite element analysis of the periodontal ligament under orthodontic tooth loading. *Am J Orthod Dentofacial Orthop* 2003; 123:657-65.
- Akpinar I, Anil N, Parnas L. A natural tooth's stress distribution in occlusion with a dental implant. *J Oral Rehabil* 2000;27:538-45.
- Kobs G, Bernhardt O, Meyer G. Accuracy of computerized axiography controlled by MRI in detecting internal derangements of the TMJ. *Stomatologija. Baltic Dent Maxillofac J* 2004; 6:7-10.
- Huang BY, Whittle T, Murray GM. Activity of inferior head of human lateral pterygoid muscle during standardized lateral jaw movements. *Arch Oral Biol* 2005;50:49-64.
- Soboleva U, Laurina L, Slaidina A. The masticatory system - an overview. *Stomatologija. Baltic Dent Maxillofac J* 2005; 7:77-80.
- Pileickiene G, Surna A. The human masticatory system from a biomechanical perspective: a review. *Stomatologija. Baltic Dent Maxillofac J* 2004; 6:81-84.
- Chen J, Akyuz U, Xu L and Pidaparti RMV. Stress analysis of the human temporomandibular joint. *Med Eng Phys* 1998;20:565-72.
- Radu M, Marandici M, Hottel TL. The effect of clenching on condylar position: A vector analysis model. *J Prosthet Dent* 2004;91:171-9.
- Naeije M, Hofman N. Biomechanics of the human temporomandibular joint during chewing. *J Dent Res* 2003; 82:528-31.

Received: 07 08 2007

Accepted for publishing: 21 12 2007