ISSN 1392 - 1207. MECHANIKA. 2010. Nr.3(83)

Influence of guiding tooth geometry on contact forces distribution in the human masticatory system: a FEM study

G. Pileičikienė*, A. Šurna, G. Skirbutis***, R. Barauskas****, R. Šurna*******
**Kaunas University of Medicine, Sukilėlių 51, 50106 Kaunas, Lithuania, E-mail g.pileicikiene@gmail.com*
***Kaunas University of Medicine, Sukilėlių 51, 50106 Kaunas, Lithuania, E-mail: surna@dent.kmu.lt*
****Kaunas University of Medicine, Sukilėlių 51, 50106 Kaunas, Lithuania, E-mail: gediminasskirbutis@yahoo.com*
*****Kaunas University of Technology, Studentų 50, 51368 Kaunas, Lithuania, E-mail: rimantas.barauskas@ktu.lt*
******Kaunas University of Technology, Studentų 50, 51368 Kaunas, Lithuania, E-mail: surna@ktu.lt*

1. Introduction

The finite element method (FEM) has become the prevalent technique used as an effective tool for analyzing all kinds of physical phenomena in structural, solid and fluid mechanics. Moreover it is used for simulating various processes in engineering in the last four decades. A remarkable advantage of the FEM is the chance to study areas that are difficult or impossible to access without any risks to a human sample [1]. The FEM has been frequently used in various fields of medical studies such as cardiovascular mechanics [2, 3], biomechanics of musculoskeletal system [5], radiofrequency ablation of liver tumors [5-7] as well as in ophthalmology [8], neurosurgery [9] and of course, dentistry [10]. Dentistry is an area of medicine where the study of human biomechanics such as chewing has the potential to improve patient care [11]. The use of FEM allows studying a single tooth, a set of teeth, or even the relationship between maxillary and mandibular dental arches; furthermore, finite element methods can be applied with the aim of improving the design of materials, structures and manufacturing procedures, leading to improved clinical results in dentistry [12]. There are already plenty reports on the modeling and stress analysis of different constituent parts of human masticatory system [10]. But still there have been very few reports that took FEM as a tool for the study of relationship between occlusal surfaces geometry and forces distribution in the whole masticatory system. Geometrical form of occlusal surfaces, spatial arrangement of teeth in dental arches and condition of supporting structures has crucial influence on masticatory function efficiency. Furthermore, proper geometry of occlusal surfaces of posterior teeth determines appropriate distribution of occlusal load to the supporting structures and normal activity of masticatory muscles and temporomandibular joints. Most of previously performed studies were directed to the relation between form of occlusal surfaces and chewing efficiency [13, 14] as well as temporomandibular joint pathology [15, 16], whereas the influence of geometrical form of occlusal surfaces in guiding teeth on forces distribution in constituent parts of masticatory system is still a little investigated field. Therefore it was decided in this study to analyze by means of FEM the influence of geometrical form of a guiding tooth on the distribution of contact forces in constituent parts of human masticatory system.

2. Three-dimensional reconstruction of skeletal and dental morphology

In order to create high accuracy three dimensional geometrical models of the main components of the investigative person masticatory system, we used our original hybrid modeling technique based on computed tomography images and three-dimensional optical scanning data [17-19].

3. The biomechanical model of masticatory system

LS-DYNA 970 finite element software (Livermore Software Technology Corporation, USA) was employed for creation of mathematical model of masticatory system. By means of surfaces triangulation hard 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. Based on accurate three-dimensional coordinates the models of individual hard parts of masticatory system were interconnected into one entirety according to general system of axes. Models of mandibular and maxillary dental arches were assumed to be whole and rigid. 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 the action of applied forces. Clenching was simulated by the action of resultant force vectors of four bilateral masticatory muscles, responsible for the elevation of the mandible, which was assumed as static occlusal load. Models of temporomandibular joint discs were generated mathematically by using a mathematical „material forming“ procedure. 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 created biomechanical model representing entire masticatory system 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 (represented by arrow triplets) and mathematically generated articular discs, ready for numerical experiments is presented in Fig. 1. Creation of computational biomechanical model of the human masticatory system was described, in detail, previously [20].

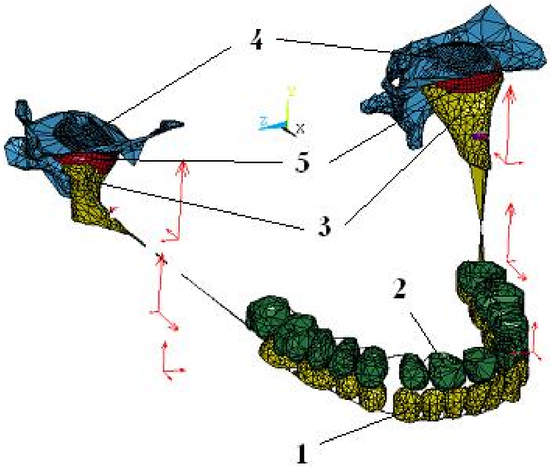
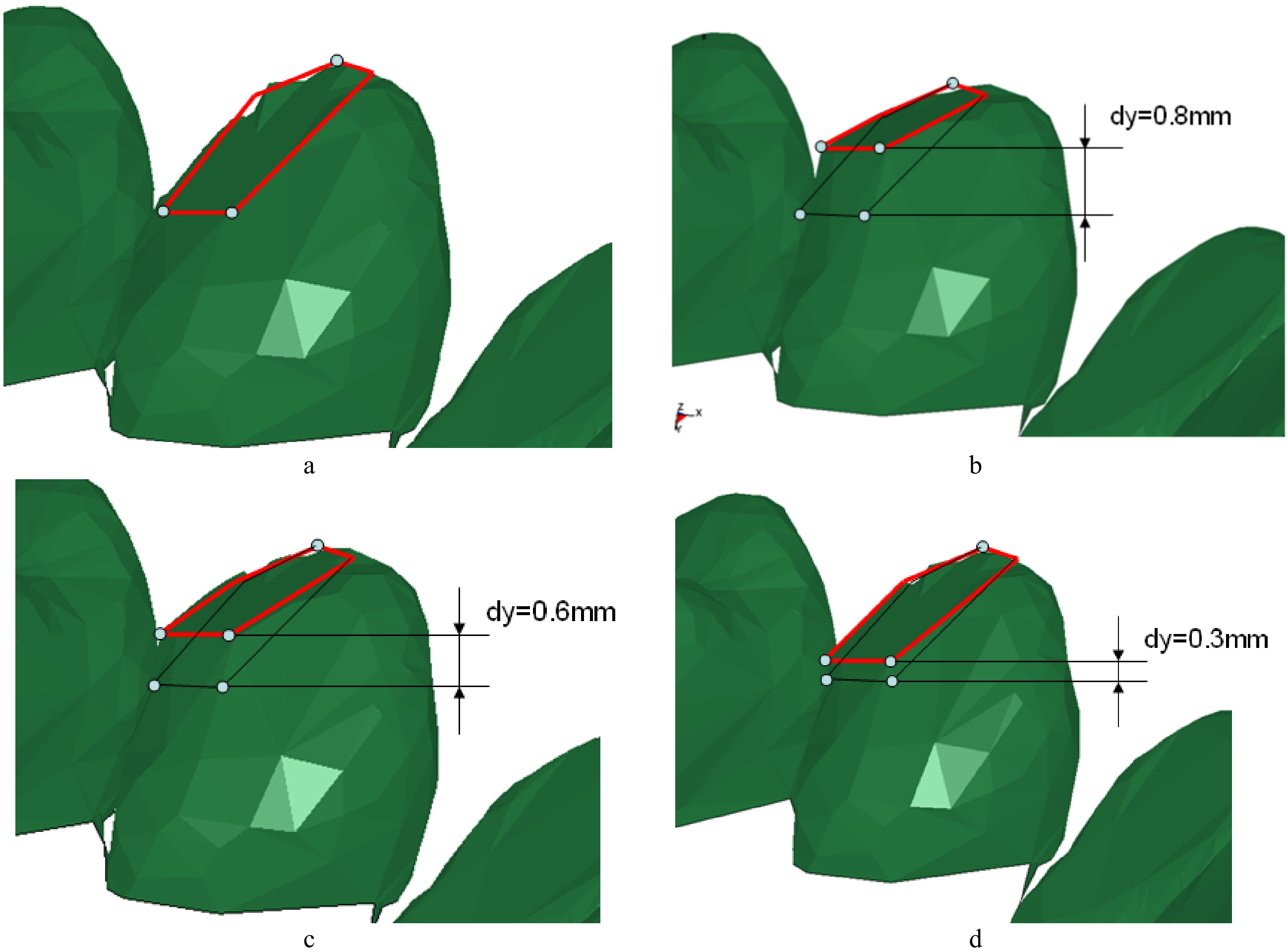


Fig. 1 Created computational model of the masticatory system: mandibular *1* and maxillary *2* dental arches, mandibular condyles *3*, mandibular fossae of temporal bone *4* and articular discs *5*

4. Investigation of guiding tooth geometry influence on contact forces distribution

4.1. Numerical experiments

In order to investigate ability of the created model of human masticatory system for the evaluation of guiding teeth geometry influence on contact forces distribution in the masticatory system we performed two numerical experiments. Based on assumption that maximum occlusal forces are generated and their redistribution is determined by the character of occlusal contacts in central occlusion, numerical experiments were performed with the created model's dental arches set into central occlusion position. Spatial relation of computational model's dental arches in the position of central occlusion was calculated mathematically, according to the nature of occlusal contacts, marked in central occlusion position on gypsum models, made by alginate impressions of the dental arches of the investigative person.



a b c d

Fig. 2 Simulated occlusal interference on guiding surface of tooth 13 in the computational model: a - corrective plane involving guiding elements; b - occlusal interference's height 0.8 mm; c - occlusal interference's height 0.6 mm; d - occlusal interference's height 0.3 mm

In order to evaluate distribution of contact forces in masticatory system of healthy subject using created model the distribution of reaction forces in maxillary dental arch and temporomandibular joint discs, generated during simulated clenching into central occlusion with non-modified geometry dental arches under action of applied force system, imitating activity of jaw closing muscles was investigated.

To evaluate the influence of guiding tooth geometry on contact forces distribution numerical experiment simulating adjustment of occlusal interference on the surface of one guiding tooth was performed. It was assumed that canine guidance is specific to the investigative subject, therefore occlusal interference on guiding surface of maxillary right canine (tooth 13) was simulated and redistributions of forces during the stages of its adjustment were investigated. Initially guiding elements on palatal surface of tooth 13 were determined and marked based on occlusal relations of gypsum models of dental arches. According to markings on gypsum model of the maxillary dental arch corrective plane involving guiding elements of tooth 13 was delineated on corresponding tooth in the computational model (Fig. 2, a). It was assumed that simulated occlusal interference was 0.8 mm height in axis Y if measured from central occlusion point on the palatal surface of the tooth. Accordingly, two points of corrective plane were uplifted in axis Y by 0.8 mm (Fig. 2, b). Adjustment of occlusal interference was simulated by changing the inclination of corrective plane; it was achieved by lowering two points of the plane in axis Y by 0.2 and 0.5 mm (Fig. 2, c and d). Therefore, simulating adjustment stages of occlusal interference on maxillary right canine, calculations were performed and force redistribution investigated with given height of 0.8, 0.6 and 0.3 mm of occlusal interference on guiding surface of tooth 13.

4.2. Results

Results of numerical experiment, performed to evaluate the influence of guiding teeth geometry on contact forces distribution in masticatory system of healthy subject with non modified geometry dental arches are presented in Fig. 3 and Table 1.

It is obvious from Fig. 3 that supreme forces acted on the posterior teeth in both sides of dental arch, articular discs were loaded nearly symmetrically and with less force; ultimate force vectors were directed along the axes of teeth, lateral vectors were negligible; and rotational moments in the centers of resistance of maxillary teeth were insignificant.

Results of numerical experiment, performed to evaluate the influence of guiding teeth geometry on contact forces distribution in simulated clinical situation with simulated occlusal interference on surface of tooth 13 are presented in Fig. 4 and Tables 2, 3 and 4.

Based on changes of reaction forces and total moments presented in Table 2 it can be stated that even minimal modification (0.3 mm) of tooth 13 guiding surface determined significant alterations of reaction forces and total moments acting the particular tooth. Among three simulated situations the most beneficial distribution of re-

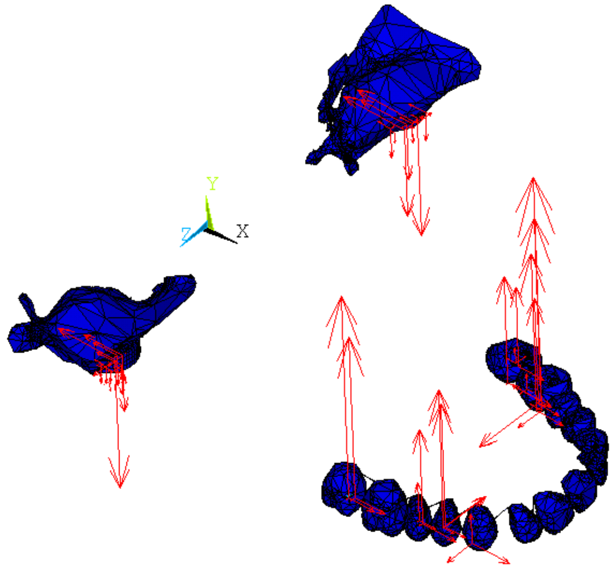


Fig. 3 Distribution of reaction forces in maxillary dental arch and temporomandibular joint discs, generated during simulated clenching with nonmodified geometry dental arches

Table 1

Reaction forces of maxillary teeth and temporomandibular joint discs, calculated during simulated clenching with nonmodified geometry dental arches

Location of force/moment in masticatory system	Total reaction force in axis X, N	Total reaction force in axis Y, N	Total reaction force in axis Z, N	Total moment in axis X, Nm	Total moment in axis Y, Nm	Total moment in axis Z, Nm
Right articular disc	–65.154	–125.211	27.459	–	–	–
Left articular disc	–77.031	–120.901	–15.531	–	–	–
Tooth 17	19.227	122.091	2.289	0.2129	–0.0392	0.1941
Tooth 27	20.496	67.718	–3.606	–0.0447	0.0412	0.2731
Tooth 16	0	0	0	0	0	0
Tooth 26	4.511	233.101	32.372	–0.9707	0.0157	0.2867
Tooth 15	17.335	44.237	2.637	0.0871	–0.0397	0.1045
Tooth 25	0	0	0	0	0	0
Tooth 14	10.331	88.087	–31.499	0.3386	–0.0576	–0.0435
Tooth 24	0	0	0	0	0	0
Tooth 13	12.928	10.078	9.863	–0.1295	0.0409	0.1279
Teeth 23, 12, 22, 11, 21	0	0	0	0	0	0
Total force on dental arch	84.827	565.311	12.057	–	–	–

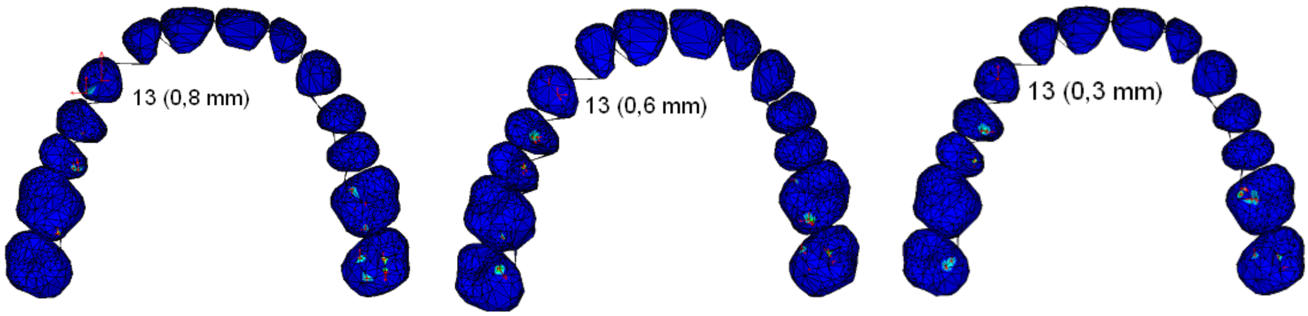


Fig. 4 Distribution of reaction forces in maxillary dental arch with simulated occlusal interference on guiding surface of tooth 13: a - height 0.8 mm; b - height 0.6 mm; c - height 0.3 mm

Table 2

Alternations of reaction forces and total moments estimated during simulated adjustment of occlusal interference (OI) on guiding surface of tooth 13

Character of tooth‘s geometry modification	Total reaction force in axis X, N	Total reaction force in axis Y, N	Total reaction force in axis Z, N	Total moment in axis X, Nm	Total moment in axis Y, Nm	Total moment in axis Z, Nm
OI=0.8 mm	86.644	51.064	10.687	–0.2605	0.1696	0.8346
OI=0.6 mm	44.656	51.472	–33.646	0.3632	–0.0568	0.3875
OI=0.3mm	30.511	28.286	4.921	–0.0602	0.0112	0.3074
Nonmodified	12.928	10.078	9.863	–0.1295	0.0409	0.1279

Table 3

Alternations of total reaction forces on whole maxillary dental arch estimated during simulated adjustment of occlusal interference (OI) on guiding surface of tooth 13

Character of tooth‘s geometry modification	Total reaction force in axis X, N	Total reaction force in axis Y, N	Total reaction force in axis Z, N
OI=0.8 mm	126.611	545.531	33.361
OI=0.6 mm	125.211	542.165	–1.253
OI=0.3mm	82.629	559.221	14.121
Nonmodified	84.827	565.311	12.057

Table 4

Alternations of reaction forces in temporomandibular joint articular discs estimated during simulated adjustment of occlusal interference (OI) on guiding surface of tooth 13

	Right articular disc			Left articular disc		
Character of tooth‘s geometry modification	Total reaction force in axis X, N	Total reaction force in axis Y, N	Total reaction force in axis Z, N	Total reaction force in axis X, N	Total reaction force in axis Y, N	Total reaction force in axis Z, N
OI=0.8 mm	–40.157	–159.891	38.873	–60.617	–106.311	–5.737
OI=0.6 mm	–25.597	–116.35	4.769	–79.239	–153.111	–15.568
OI=0.3mm	–64.881	–128.61	30.561	–79.941	–123.591	–17.004

action forces was established when simulated occlusal interference was of height 0.3 mm, because forces acting on the tooth in axis Z decreased and proportions between forces acting in axes X and Y persisted similar as were estimated without modification of tooth’s geometry. However, even such small occlusal interference (0.3 mm) caused approximately three times increment of forces acting in axes X and Y. Values of tooth’s 13 rotational moment’s components in three axes indicated that diminishing of simulated occlusal interference changed not only spatial orientation of tooth’s rotational axis but also its tendency of rotation; while strong tendency of driftage forward was observed during all the stages of numerical experiment.

Evaluation of total reaction forces showed that with lowering the simulated occlusal interference total reaction forces of maxillary dental arch gradually decreased in axis X and increased in axis Y, while their effects in axis Z changed unevenly; this was caused by significant change of magnitude and direction of lateral force arisen in teeth 13 when simulated occlusal interference was of height 0.6 mm (Table 3).

During all the stages of numerical experiment the character of reaction forces in temporomandibular joint articular discs changed together with the modification of simulated adjustment of occlusal interference height (Table 4). With non modified geometry of tooth 13 it was established that both articular discs were loaded nearly equally in axes X and Y; while magnitudes of forces in axis Z differed almost twice. The higher was the simulated occlusal interference the stronger vertical forces (in axis Y) affected right articular disc and the slighter vertical forces acted on left articular disc; forces in axis X decreased in both articular discs while lateral forces in axis Z increased almost twice in right and decreased almost three times in left articular disc.

5. Conclusions

In accordance with results of the performed numerical experiments it can be stated that simulated occlusal interference on guiding surface of tooth 13 determined significant changes of magnitudes and directions of forces acting the tooth and influenced its tendency for driftage; also caused changes in loading of the temporomandibular joint discs and alternated character of total forces acting on the whole maxillary dental arch. The evaluation of forces alternations during simulated stages of occlusal interference adjustment demonstrated that the most beneficial distribution of reaction forces was established when simulated occlusal interference was reduced to minimal height of 0.3 mm. However, even such diminutive occlusal interference (0.3 mm) caused significant increment of deleterious lateral forces. Consequently, the created three-dimensional finite element model of masticatory system showed satisfactory efficiency for the evaluation of forces, acting on guiding tooth when its geometry is modified, because even minimal error (0.3 mm) of simulated occlusal adjustment caused non physiological redistribution of forces both in guiding tooth and in temporomandibular joint discs.

References

1. **Jeon, P.D., Turley, P.K., 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, p.498-504.
2. **Mackerle, J.** Finite element modelling and simulations in cardiovascular mechanics and cardiology: A bibliography 1993–2004. -Computer Methods in Biomechanics & Biomedical Engineering, 2005, 8, p.59 -581.
3. **Sermesant, M., Forest, C., Pennec, X., Delingette, H., Ayache, N.** Deformable biomechanical models: Application to 4D cardiac image analysis. -Medical Image Analysis, 2003, 7, p.475-488.
4. **Michnik, R., Jurkojć, J., Pauk, J.** Identification of muscles forces during gait of children with foot disabilities. -Mechanika. -Kaunas: Technologija, 2009, Nr.6(80), p.48-51.
5. **Barauskas, R., Gulbinas, A., Barauskas, G., Vanagas, T.** Finite element modeling of cooled-tip probe radiofrequency ablation processes in liver tissue. -Computers in Biology and Medicine, 2008, 38(6), p.694-708.
6. **Barauskas, R., Gulbinas, A., Barauskas, G.** Investigation of radiofrequency ablation process in liver tissue by finite element modeling and experiment. -Medicina. -Kaunas, 2007, 43(4), p.310-325.
7. **Barauskas, R., Gulbinas, A., Barauskas, G.** Finite element modeling and experimental investigation of infiltration of sodium chloride solution into in-vitro liver tissue. -Medicina. -Kaunas, 2007, 43(5), p.399-411.
8. **Sukhun, J.A., Lindqvist, C., Kontio, R.** Modelling of orbital deformation using finite-element analysis. - J. R. Soc. Interface, 2006, 3, p.255-262.
9. **Gao, C., Tay, F.E.H., Nowinski, W.L.** A Finite Element Method Based Deformable Brain Atlas Suited for Surgery Simulation. -Engineering in Medicine and Biology Society, 2005, p.4337-4340.
10. **Mackerle, J.** Finite element modelling and simulations in dentistry: a bibliography 1990-2003. -Comput Methods Biomech Biomed Eng, 2004. 7, p.277-303.
11. **Correia, A., Piloto, P., Campos, J.C.R., Vaz, M.** Finite element analysis of the mechanical behavior of a partially edentulous mandible as a function of cancellous bone density. -Rev. Odonto Ciênc, 2009, 24(1), p.22-27.
12. **Alemzadeh, K.** Dento-Munch and dento-OS inventions. Digital Dental News, 2009, 3, p.28-33.
13. **Bourdiol, P., Mioche, L.** Correlations between functional and occlusal tooth–surface areas and food texture during natural chewing sequences in humans. -Arch Oral Biol, 2000, 45(8), p.691-699.
14. **Ciancaglini, R., Gherlone, E.F., Radaelli, G**. Association between loss of occlusal support and symptoms of functional disturbances of the masticatory system. -J Oral Rehabil, 1999, 26, p.248-253.
15. **Sato, S., Ohta, M., Sawatari, M., Kawamura, H., Motegi, K.** Occlusal contact areas, occlusal pressure, bite force and masticatory efficiency in patients with anterior disc displacement of the temporomandibular joint. -J Oral Rehabil, 1999, 26, p.908-911.
16. **Tanaka, E., Tanaka, M., Watanabe, M., Del Pozo, R., Tanne, K.** Influences of occlusal and skeletal discrepancies on biomechanical environment in the TMJ during maximum clenching: an analytic approach with the finite element method. -J Oral Rehabil, 2001, 28, p.888-894.
17. **Šurna, R.** A three-dimensional model of the masticatory system. -Proc. of 12th Int. Conf. “Mechanika 2007”. -Kaunas, 2007, p.203-207.
18. **Šurna, R.** Creation of 3D model of human masticatory system. -Proc. of 13th Int. Conf. “Mechanika 2008”. -Kaunas, 2008, p.213-217.
19. **Pileičikienė, G., Šurna, A., Skirbutis, G., Šurna, R., Barauskas, R.** A new technique for the creation of a higher accuracy 3D geometrical model of the human masticatory system. -Mechanika. -Kaunas: Technologija, 2009, Nr.4(78), p.44-50.
20. **Pileičikienė, G., Šurna, A., Barauskas, R., Šurna, R., Basevicius, A.** 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. -Stomatologija, Baltic Dental and Maxillofacial Journal, 2007, 9, p.121-128.

G. Pileičikienė, A. Šurna, G. Skirbutis,
R. Barauskas, R. Šurna

VEDANČIOJO DANTIES GEOMETRINĖS FORMOS ĮTAKOS SĄLYČIO JĖGŲ PASISKIRSTYMUI ŽMOGAUS KRAMTYMO SISTEMOJE TYRIMAS BAIGTINIŲ ELEMENTŲ METODU

R e z i u m ė

Tyrimo tikslas – nustatyti vedančiojo danties geometrinės formos įtaką sąlyčio jėgų pasiskirstymui žmogaus kramtymo sistemoje. Tuo tikslu LS-DYNA programine įranga, remiantis realiais geometriniais duomenimis, sukurtas erdvinis skaičiuojamasis kramtymo sistemos modelis. Baigtinių elementų metodu atlikta imituojamo priešlaikinio okliuzinio kontakto koregavimo analizė. Iš skaitinių eksperimentų rezultatų matyti, kad esant net minimaliam imituojamo priešlaikinio kontakto aukščiui 13-ojo danties vedančiajame paviršiuje smarkiai keičiasi 13-ąjį dantį veikiančių jėgų dydžiai ir kryptys. Taip pat keičiasi danties poslinkio tendencija, sąnarinių diskų apkrova ir visą dantų lanką veikiančių suminių jėgų pobūdis.

G. Pileičikienė, A. Šurna, G. Skirbutis,
R. Barauskas, R. Šurna

INFLUENCE OF GUIDING TOOTH GEOMETRY ON CONTACT FORCES DISTRIBUTION IN THE HUMAN MASTICATORY SYSTEM: A FEM STUDY

S u m m a r y

The paper presents the numerical investigation with the purpose to find correlation between geometrical form of a guiding tooth and distribution of contact forces in the human masticatory system. The 3D computational model of masticatory system based on real geometrical data was built by means of LS-DYNA finite element software. The FEM analysis of simulated occlusal interference adjustment was performed. Results of numerical experiments showed that even minimal height of simulated occlusal interference on guiding surface of tooth 13 determined significant changes of magnitudes and directions of forces acting on the tooth and influenced its tendency for driftage; also caused changes in loading of the temporomandibular joint discs and alternated character of total forces acting on the whole maxillary dental arch.

Г. Пилейчикене, А. Шурна, Г. Скирбутис,
Р. Бараускас , Р. Шурна

ВЛИЯНИЕ ГЕОМЕТРИЧЕСКОЙ ФОРМЫ ВЕДУЩЕГО ЗУБА НА РАСПРЕДЕЛЕНИЕ КОНТАКТНЫХ СИЛ В ЖЕВАТЕЛЬНОЙ СИСТЕМЕ ЧЕЛОВЕКА: КОНЕЧНОЭЛЕМЕНТНОЕ ИССЛЕДОВАНИЕ

Р е з ю м е

Целью данной работы являлось исследование влияния геометрической формы ведущего зуба на распределение контактных сил в жевательной системе человека. Трехмерная математическая модель жевательной системы, основана на реальных геометрических данных, была построена с использованием программной установки LS-DYNA. Проведён конечноэлементный анализ имитационной коррекции преждевременного окклюзионного контакта. Полученные результаты показали, что даже минимальная высота имитированного преждевременного окклюзионного контакта на ведущей поверхности 13 зуба стала причиной значительных перемен величины и направления сил, действующих на зуб, также изменила тенденцию его перемещения, нагрузку на суставные диски и характер тотальной силы, действующей на всю зубную дугу.

Received February 10, 2010
Accepted May 20, 2010