Stomatologija, Baltic Dental and Maxillofacial Journal, 17: 13-20, 2015

A revised approach of human mastication function rehabilitation through monotypical mastication analysis

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SUMMARY

Objective. The aim of the simulation was to find the forcing laws, which provide the close-to reality mastication motions of the components of the system and to investigate the contact zones, interaction forces and their action points as they vary in time. The loss of one or few elements of the mastication system can be restored without significant violations of the overall function provided the general correlations among the mastication system elements, which were influenced during the evolutionary development, have been determined in advance.

Materials and methods. We present an approach based on the computer simulation of mastication biomechanics on the basis of finite element (FE) models. They were generated by using the data acquired with both optical and CT scanning systems, which enabled to obtain highly accurate three-dimensional geometrical models of all hard parts of the mastication system of a real dead goat. The surfaces of dental arcs of upper and lower jaws mechanically interacting one against another have been used as the main parts of the model.

Results. Using FE models we discovered that mastication forces are correlated directly between dental arches and TMJ surfaces. Factors influencing geometry of dental arches results a destroy jaw function.

Conclusion. In the course of this analysis the mastication system of a goat has been considered as a representative of the ruminant individual and enabled to demonstrate the mechanics of the mastication process with insights for evaluation of the similarities and differences against the human mastication.

Keywords: Mastication biomechanics; finite element models, physicaly based simulation, mastication process.

INTRODUCTION

The masticatory system of carnivores focuses only on the rotary movements of the lower jaw (1). The joint works as a staple, or a horizontal axis, similar to the double hinge. The temporomandibular surfaces are framed by the edges of the bones and cannot perform the anterior-posterior turns. They prevent retrusion and lateral movements, even at maximum opening of the mouth (2).Unlike carnivores, the masticatory system of herbivores in the process of development acquired the joint-wise structural elements, which are able to perform specific horizontal chewing movements (3). The main evolutionary argument is the harmony of form and function ensuring the possibility of rational nutrition as one of the most important activities of an individual (4).

The human diet is of a mixed nature. Furthermore, a human has the phonetic articulation abilities and therefore he is unique individual in the living nature. The mastication and articulation systems are characterized by different biomechanical properties. They determine a particular structure of the joint (5). There is a concordance between the functional structure of the joint and the form of DA.

It enables to present the craniofacial biomechanics in its real and enables to plan the surveillance and treatment for dental patients (6). The investigation of the masticatory process of an animal can be presented as the dynamic mechanical contact problem (7). Two-

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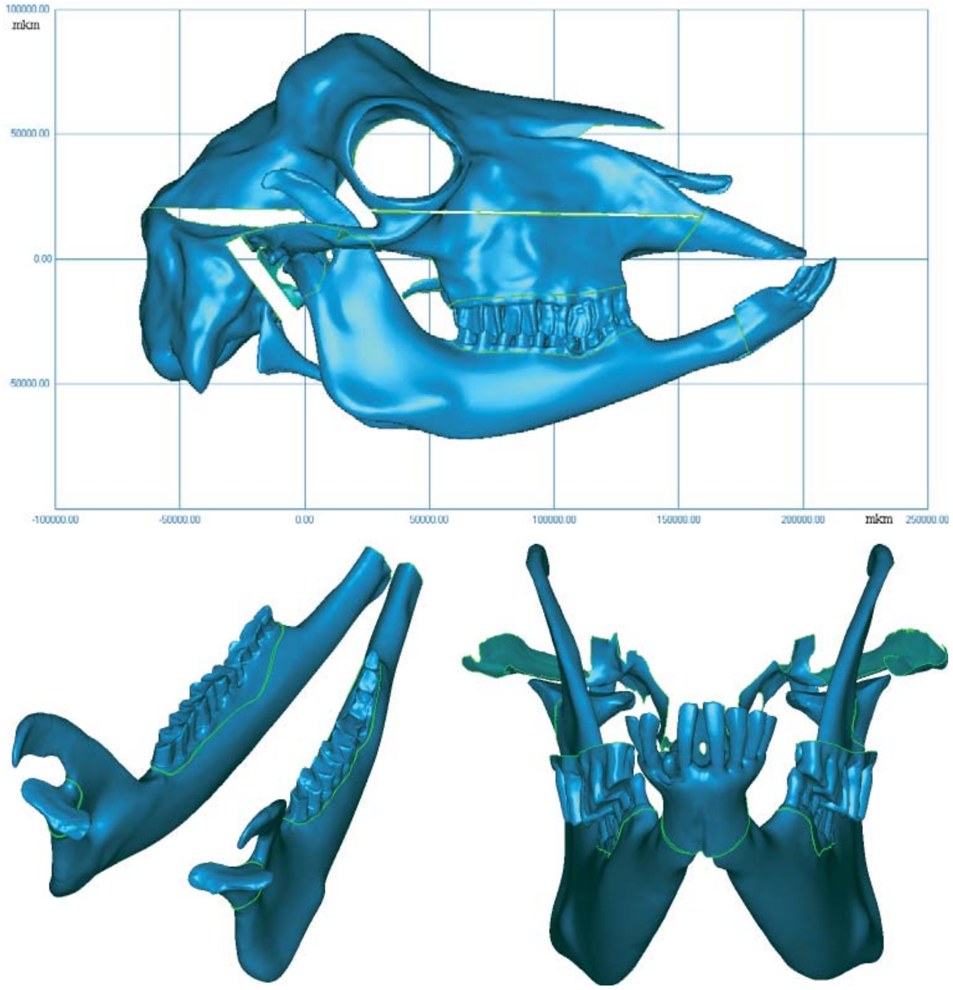

Fig. 1. Scanned surfaces of the skull of a goat

and three-dimensional (2D and 3D) finite element models were applied to the biomechanical analysis of mastication (7-10). Mathematical modelling was employed for prediction of muscles activities and jaw motion in the course of the mastication process (11). Comparisons of actual and predicted muscles forces and jaw motions were performed in order to evaluate their possible synergy or antagonism for the particular patient (12). The sensory control of human mastication is more vulnerable than the structural elements, the changes of which are very slow. The perfect harmony of the structure and function minimizes the need for protective reflexes (13).

Our work presents the finite element (FE) analysis results of chewing biomechanics of a goat as a typical representative of the herbivores (ruminating). The results of the calculations present the time laws of 3D motion of all points of the parts of the model, as well as, the locations and values of contact interaction force vectors and pressures developed over contact zones of the teeth surfaces. The knowledge of them within higher volumes of masticatory rehabilitation processes can be employed in order to re-create the functional harmony by minimizing the impact on the sensory control, as well as, enable to investigate the basic features and properties of the masticatory process of ruminating animals in order to understand their biomechanical structure naturally developed during the evolutionary process.

MATERIALS AND METHODS

We used a skull of a goat obtained from Veterinary clinic of the University of Health Sciences of Lithuania under agreement No 01/2012 and utilised according the requirements of National Animal Welfare Law. The geometry of masticatory and joints surfaces of the goat has been obtained by using the data acquired with both optical and CT scanning systems, which enabled to obtain highly accurate three-dimensional geometrical models of all hard parts of the mastication system of the head of a dead animal, (Fig.1). The scanned surfaces have been triangulated and the finite element model containing ~280000 nodes and ~550000 rigid shell elements has been developed in LS-DYNA finite element software, (Fig.2). The frontal teeth of the animal were removed from the model as they never come into immediate contact during mastication.

The computational model is presented as four-part system, which represents lower and upper DA and joints. (Fig.3) The lower DA and joints are regarded as a single rigid lower jaw, therefore the two parts are rigidly linked to each other by means of appropriate constraint equations. Three auxiliary nodes as Central control node (NC), left and right attachment nodes (NR and NL), which approximately correspond to the geometrical centre of the lower jaw and to the centres of the heads of the left and right joints are rigidly constrained to the lower jaw as hypothetic placements of resultant muscles actions developed on the system. The upper DA and joints are fixed in space and represent reference surfaces of the upper jaw, over which the contact sliding motion of the lower jaw surfaces takes place. Three

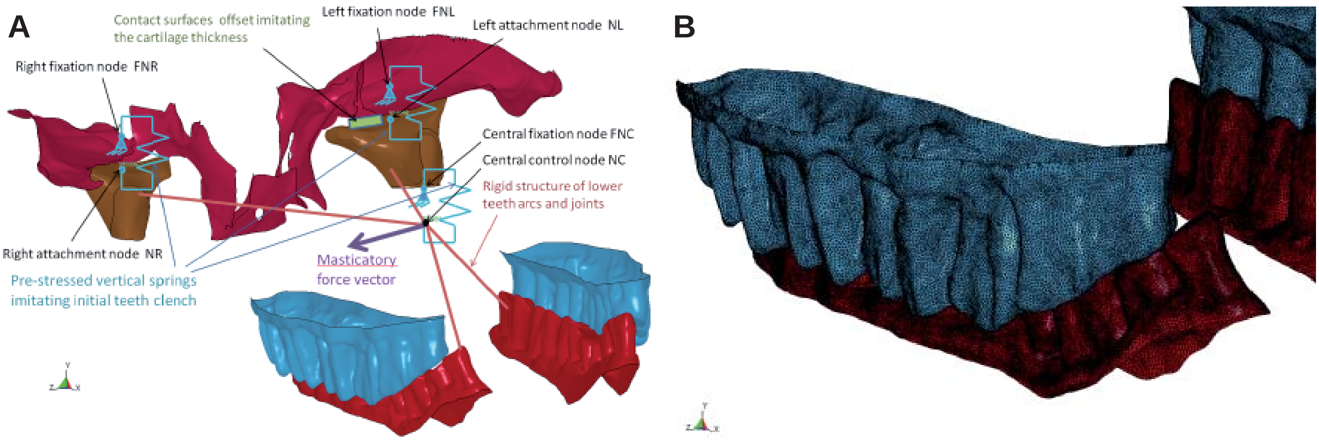

Fig. 2. Geometry of the main parts of the mechanical contact model of the two jaws (A) and the finite element mesh (B)

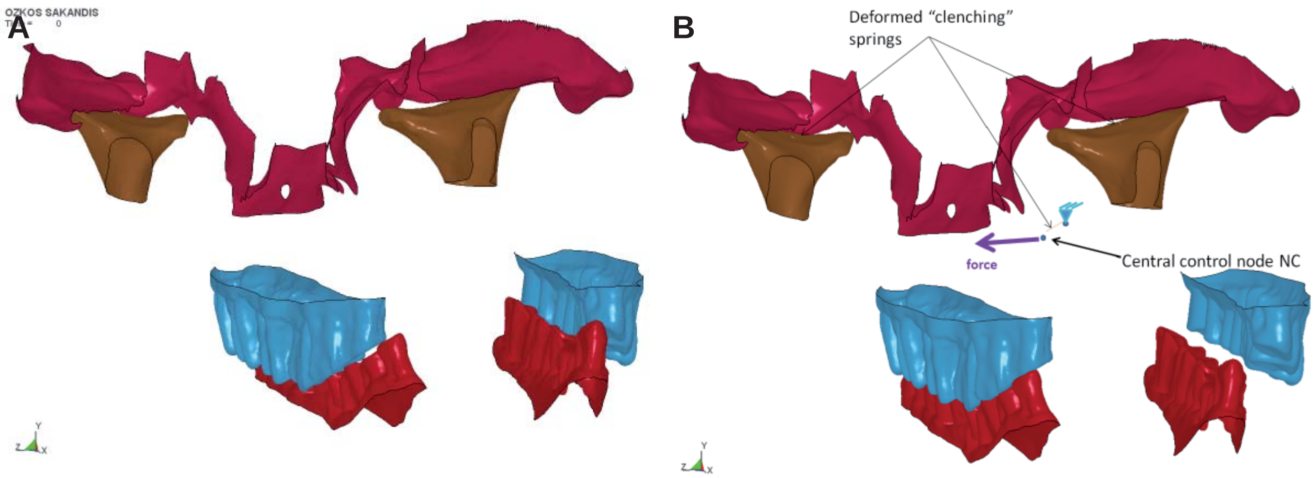

Fig. 3. Initial clench position (A) and the position after the side motion of the lower jaw (B) as a result of the action of the force applied at node NC

auxiliary fixation nodes FNC, FNR and FNL, which initially have identical locations as nodes NC, NR and NL, were constrained to the upper jaw. Node NC is employed as the control node, to which the resultant force causing the motion of the lower jaw is applied. No periodontal flexibility of the teeth has been considered in this study.

The contact interaction conditions in the finite element model are described by means of penalty-based automatic contact treatment between the nodes of one surface against the element surfaces of the other. The penalty stiffness is selected large enough in order to prevent perceptible penetrations of the surfaces into each other. Moreover, the penalty stiffness employed in the finite element model can be interpreted as an estimation of the real stiffness of the teeth surface combined with the elastic compliances of the teeth due to their soft periodontal positioning. In this model the penalty spring stiffness is assumed as 60000 N/m at each contacting node.

We simulated the mastication movement by applying the Oz-directed force vector at the central control node NC, which is constrained to the lower jaw, simultaneously with the initial clenching forces caused by the pre-strained springs. The resulting mastication motion resembles sliding of the lower jaw against the upper one and is similar to teeth-grating.

The contact zones between the DA and between the surfaces of the lower and upper joints change all the time as the jaw performs the mastication movement. At any time instant the contact takes place only in several local zones over the teeth surfaces. For the sake of analysis the contact force systems acting at the right and left dental arcs (RDA and LDA) and right and left joints (RJ and LJ) are replaced by their resultants as follows.

The action of force system $\vec{\mathbf{F}}_i$ acting at points $\vec{\mathbf{r}}_i$, $i = 1, 2, ..., n$, where n is the number of forces, is equivalent to the action of resultant force $\vec{\mathbf{F}} = \sum_{i=1}^{n} \vec{\mathbf{F}}_i$ and resultant couple $\vec{\mathbf{M}} = \sum_{i=1}^{n} \left(\vec{\mathbf{r}}_i \times \vec{\mathbf{F}}_i \right)$ acting at the origin of the coordinate system. Resultant couple $\vec{\mathbf{F}}$ can be presented by the vector sum of two components, one collinearand one perpendicular to vector $\vec{\mathbf{F}}$ as $\vec{\mathbf{M}} = \vec{\mathbf{M}}_c + \vec{\mathbf{M}}_p$, where

$$\vec{\mathbf{M}}_c \parallel \vec{\mathbf{F}}, \quad \vec{\mathbf{M}}_c = \left(\vec{\mathbf{M}} \cdot \vec{\mathbf{F}} \right) \frac{\vec{\mathbf{F}}}{\left| \vec{\mathbf{F}} \right|},$$

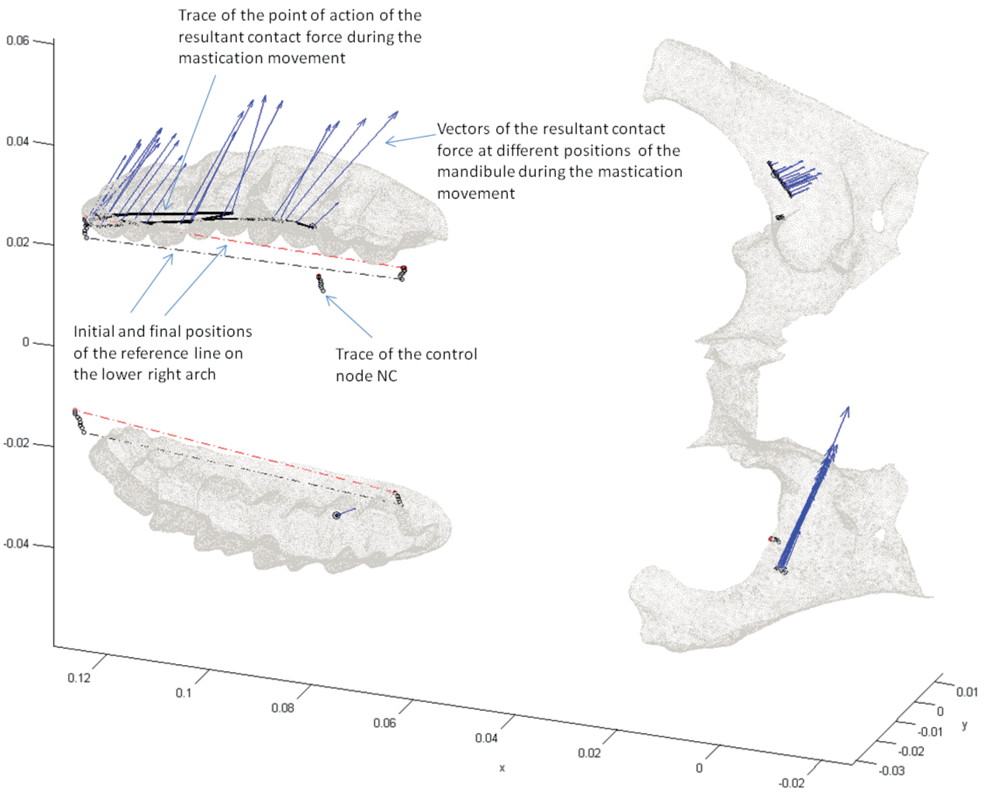

Fig. 4. The traces of the points of action of the resultant interaction forces between the teeth arcs and joint surfaces during the mastication movement of a healthy goat

$$\vec{\mathbf{M}}_p \perp \vec{\mathbf{F}}, \quad \vec{\mathbf{M}}_p = \vec{\mathbf{M}} - \vec{\mathbf{M}}_c.$$

The position vector of the point of action of the resultant is obtained as

$$\vec{\mathbf{r}} = \frac{|\vec{\mathbf{M}}_p|}{|\vec{\mathbf{F}}|} \cdot \frac{\vec{\mathbf{F}} \times \vec{\mathbf{M}}}{|\vec{\mathbf{F}} \times \vec{\mathbf{M}}|}.$$

The numerical experiment is carried out in order to analyse the change of the contact conditions between the lower and upper jaws as the force in the direction Oz is applied at control node NC. As a result of the action of the force, the side displacement of the frontal part of the lower jaw, as well as, the rotation of the rigid structure of the lower jaw about the vertical axis is produced. The magnitudes of the displacements to be investigated were approximately determined by analysing a video of the masticating animal. The forces developed during the mastication of a healthy animal (Fig. 5a) were compared against the hypothetical situation, where the lower RDA was situated 4 mm below its proper position (Fig.5b).

RESULTS

We obtained the initial clench position of the jaws by applying the forces in the clenching direction (direction Oy in this model) by means of three elastic springs pair-wise attached between the nodes NC,NR, NL of the lower jaw and the corresponding nodes FNC,FNR,FNL fixed at the upper jaw. The initial pre-straining of the springs developed the contractive action between the jaws and forced them to fall into the initial clench in accordance with the tubers of both mastication surfaces. In this model the stiffness of each longitudinal Oy spring was assumed as 50000 N/m, and the pre-straining was 0.013m, which corresponded to 659N total clenching force.

In order to excite the motion of the lower jaw constant Oz-directed force was applied to node NC. (Fig.4) demonstrates the relative positions of the lower and upper jaws at the beginning and the end of the simulation process. The pre-stressed mathematical springs acting pair-wise along axis Oy in-between auxiliary nodes NC, NR, NL and FNC, FNR, FNL are initially invisible because of their zero length (Fig.3a).

At the final position (Fig.3b) the springs are elongated and change their directions because of the displacement of the jaw. The spring at node NC exhibits the resistance to the side motion of the lower jaw and finally limits its displacements because of the achieved equilibrium of elastic, contact and external forces in all directions. The loss of contact at the LDA takes place as the jaw turns to the right.

Fig.4 presents the traces of the points of action of the contact forces resultants exhibited on each DA and each joint during the mastication movement shown in Fig.3a as an initial position and Fig.3b as the final position. The arrows in Fig.4 display the resultant contact forces exerted on the upper jaw by the lower jaw at each time moment during the mastication movement. Not only the magnitudes but also directions of the resultant forces change in time as the jaw moves. The change of the direction takes place due to slightly different directions of contact forces at different points of the curved and seemingly irregular tubers of teeth surfaces. The resultant couples created by contact interaction forces are not presented in Fig.4 because of their minor significance

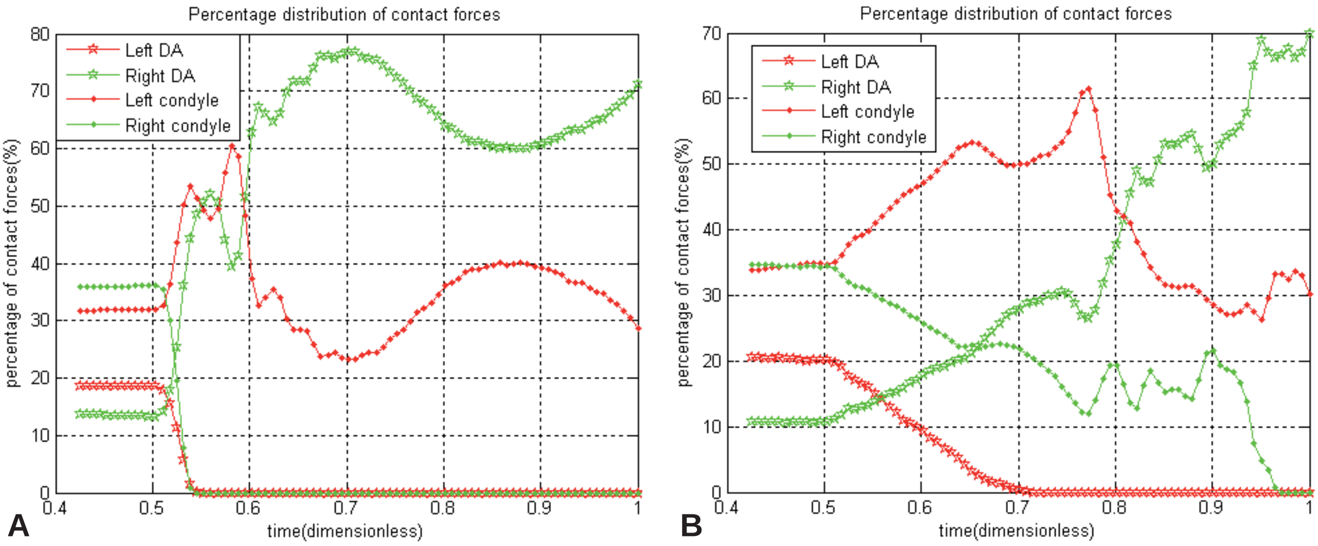

Fig. 5. Time-relationships of percentage distribution of vertical components of the resultant forces at the teeth arcs and at the joints during the side motion of the jaw of a healthy goat (A) and in case the right lower dental arch is displaced through 4mm downwards with respect to its proper position (B).

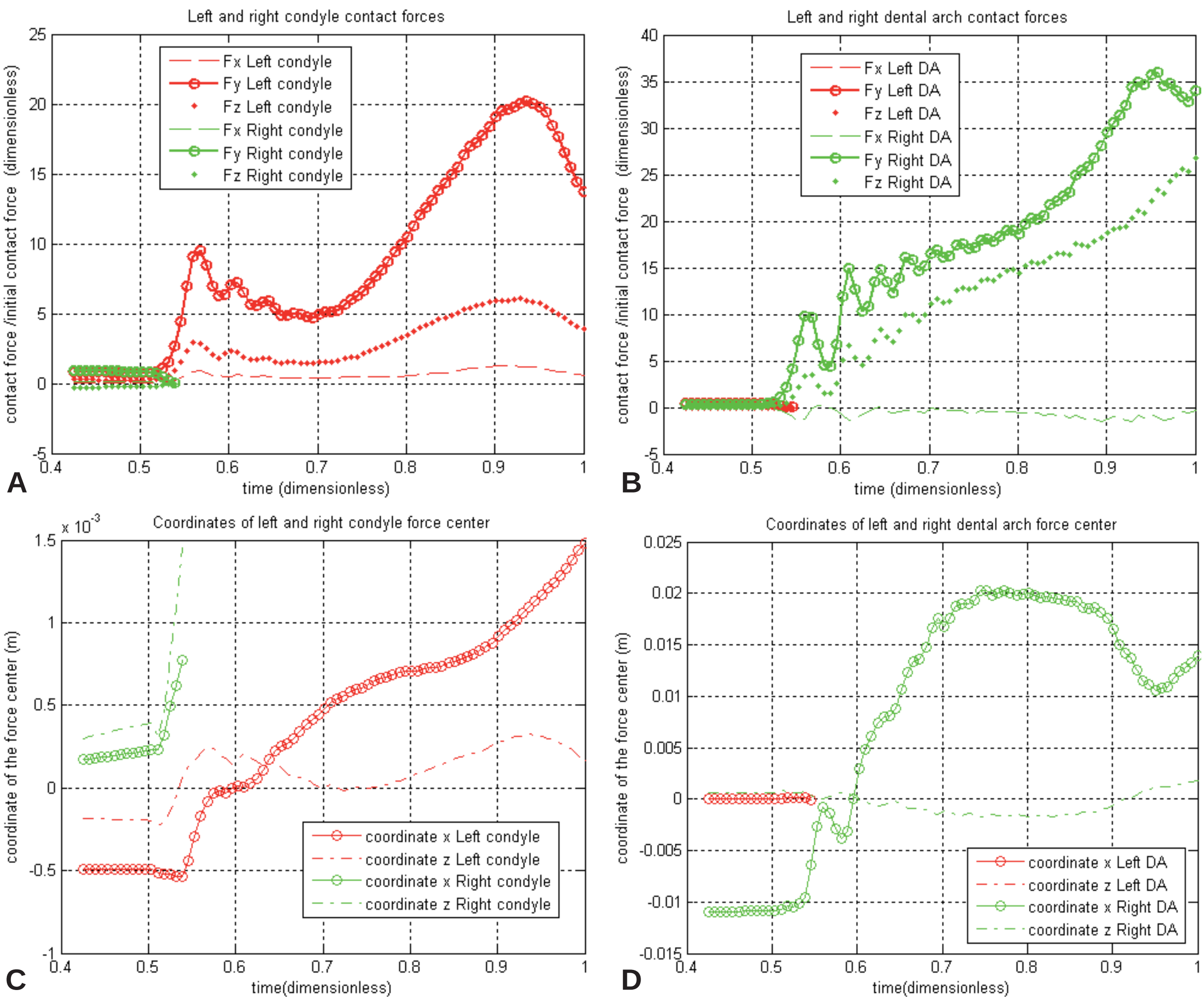

Fig. 6. Time-relationships of dimensionless resultant contact forces over dental arches and the joints (A and B) and changes of the coordinates of point of action of the resultants (and D) during the imitated sideways motion of the lower jaw of a healthy animal.

in comparison with the biomechanical influence of large compressive contact forces.

The time-relationships of percentage distribution of vertical components of the resultant forces

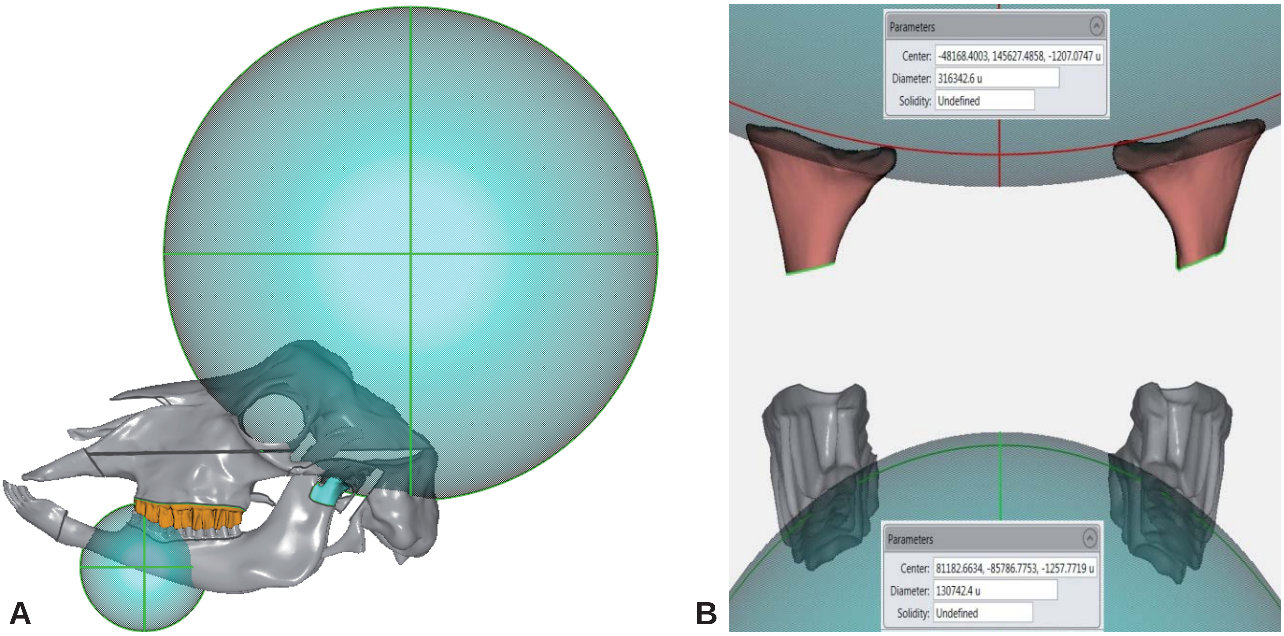

Fig. 7. Spherical surfaces approximating the overall geometry of the articular surfaces and the occlusal surfaces of the teeth arches of a goat. General view (a) and the frontal projection (b).

are presented in Fig.5. Fig. 6a,b presents the time-relationships of the dimensionless resultant contact forces (instantaneous force values divided by the initial clenching force). Fig. 6c,d presents the time-relationships of the coordinates of point of action of the resultants.

DISCUSSION

The study of a limitary case may provide a deeper insight into the evolution of bone structures of the human mastication system. We didn‘t find any data about the interactions of contact forces within the ruminating animals in the literature. A goat was chosen as a representative of them due to its mono-typical function of mastication, by which horizontal milling movements of the lower jaw dominate. Regardless the mono-typical mastication function, in which the horizontal Oz directed motions prevail provided the sufficient stress in Oy direction is developed, the active surfaces of main supporting structures are situated on an approximating spherical surface rather than on the horizontal plane. The cheek tubers of upper molars of a goat are up to 5mm lower than the lingual tubers. Therefore the occlusive surfaces of the molars form the mean sphere centred below the body of the lower jaw. The overall geometry of the surfaces of the joints can be approximated by the surface of a significantly larger sphere centred above the DA and displaced in the distal direction.

Such geometry of the active mastication surfaces enables to consider that the unilateral mastication mode dominates by the ruminating animals (16). The orientation of two supporting structures on the surfaces of two different spheres situated below and above the jaws prevents the localization of the working and balancing zones at the occlusive surfaces of the DA.

Human surfaces of the joints and of the occlusion surfaces are situated on the sphere, the centre of which is situated above the jaws and can be considered as the rotation centre of the lower jaw. The human mastication system is two-lateral. It contains the working and balancing sides. Presumably such type of a system is more universal and adjusted to the mixed nutrition type. Very probably the analysis of contact forces developed in supporting elements could be informative for determining the correlation between the forms of the mastication surfaces and the distributions of the mastication forces over the DA and joints.

A different treatment of the contact interaction is necessary between the surfaces of the lower and upper joints. The contact interaction between the joints takes place via the cartilages, which in live animals reside in-between the lower and upper joints surfaces. The geometry of the cartilages could not be obtained from the scans of the surfaces as it is not a bone structure. Moreover, the true thickness of the cartilage cannot be obtained from the scan as the mutual positions of the joints surfaces of a dead animal is different compared with the real-life situation. We assume the cartilage thickness as ~1.4mm, which is taken into account in the finite element model by applying the thickness offsets 0.7mm of the contacting surfaces of the lower and upper joints. This means that shell thickness is taken into account when treating the contact penetrations between the two surfaces checked at every time step during the simulation. In addition, small sliding friction coefficient value 0.02 was applied in order only to prevent the destabilization of the motions of the lower jaw, as it moves under action of the applied forces.

The analysis of the mastication forces of a goat as a representative of the mono-typically masticating herbivores demonstrated the distribution of the clenching forces and the re-distribution of them in the course of the side motion, as well as, due to the position change (lowering) of the occlusion plane. During the static clench (the interval in Fig.5a up to dimensionless time 0.5) the percentage distribution of the occlusion forces is symmetrical over left and right sides of the supporting structures. The right-hand side contact forces are localized as 36% of the total force on the joint and 14% on the DA at both sides. At the left-hand side the joint takes 32% of the force and the DA 18%.

In the course of the occlusion to the right a marked redistribution of contact forces magnitudes and localization takes place. The main load is intercepted by the RDA and LJ (the interval 0.5 to 0.8 in Fig.5a). The loss of contact is observed between the LDA and in the RJ. The analysis of the contact forces demonstrated that they are synchronically oriented along Oy and Oz directions, Fig.7. Magnitudes of Oz–oriented forces are not small because of the spherical form of the occlusion surface. Such orientation of the occlusion surfaces of the working side enables to localize the forces developed by muscles at the working side and ensures the maximum efficiency of the „quern“.

In case the lower RDA is shifted downwards 4mm, the initial central occlusion develops the contact interactions over three zones only. However, immediately the forced imbalanced self-correction of the dislocation takes place. In both joints forces of approximately equal magnitude are established (Fig.5b), however the coordinates of the point of action of the resultant change through 3-4mm. In case of the comparatively flat surface of the joint of a goat the displacement does not have any significant influence on the direction of the resultant force, which is normal to the surface of the joint. Bearing in mind of human case, the displacement of the contact point along Ox should result in significant changes of the height and therefore the marked re-distribution of the contact forces. In the course of the right-hand side occlusion the contact is being lost at LDA. The cheek tubers of the upper RDA, the lingual tubers of the RDA and LJ are the main supporting surfaces.

The human mastication system contains features of both herbivores and carnivores. On the other hand, due to hazardous influence of scanning on live individuals numerous experiments are hardly possible with humans, however, are possible with dead animals. The results about the distribution of forces developed in the mono-typical mastication system of a goat presented discovered the mutual correlation of structures taking part in the mastication process in this work. The unilateral mastication type ensuring the rumination function excludes the contact of DA of another side. The forces ensuring the equilibrium may be interpreted as situated on the vertices of a triangle formed by both joints and one DA. The mastication forces are balanced at the opposite joint with app. 50% more (Fig.5a,b). The change of the spatial position of the occlusion surface is followed by the change of the spatial localization of contact forces therefore the balance is disturbed.

CONCLUSIONS

The analysis enabled to better understand and predict the dependences of contact forces distribution against possible deviations of the occlusion surfaces spatial positions and therefore may be useful for planning the restitution of the lost parts of DA and the rehabilitation also by humans, who possess a complex bilateral mastication system.

LIMITATIONS

The finite element models provide highly adequate results in case proper geometry, boundary conditions and forcing laws are applied. In our case the 3D free-form surfaces of the mastication system are obtained with the precision sufficient to most practical investigation needs. Unfortunately, there remain other functional details of the overall model, which cannot be measured directly. They introduce uncertainties, which may affect the computed results and to diminish their adequacy to the reality. Therefore a successful choice of the overall model architecture is the key prerequisite for the success of the investigation.

In this study we were mainly concerned with the variation in time of the magnitudes and positions of the developed resultant contact forces, as well as, with the distribution of the contact zones over the mastication surfaces of LDA and RDA and over the joints surfaces, as certain rumination motions take place and the surfaces are sliding and rubbing against each other. We assume that every analysed mastication motion begins at the initial full clenching position, and the developed clenching force is acting all the time in the side direction Oz. Additional forces applied in the plane Oz may cause other jaw motions. Such motions could be the elliptical sliding path, caused by the combination of close-to-sinusoidal Ox and Oz forcing components acting with proper amplitudes and phases.

ACKNOWLEDGEMENTS

The authors thank prof. habil.dr. Algimantas Matusevicius for professional support and consultations.

There is no known conflict of interest.

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Received: 19 11 2014
Accepted for publishing: 25 03 2015