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BIOMECHANICAL ANALYSIS OF FORCES AND MOMENTS GENERATED IN THE MANDIBLE

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Summary. *The forces generated during the function of the stomatognatic system act to the jaw bones in different directions depending on action of muscles which do definite action. The objective of this study is to determine distribution of the forces and their moments in some parts of a toothless mandible during simulation of one-sided ridge loading in the region of the lateral teeth. The chosen researching method is a combination of the clinical and the analytical (mechanically-mathematics) parts. The obtained resellers show that the forces are unevenly distributed along the jaw both on the left and right side, by which they are of the higher intensity on the side where the loading acts. The force* F_{tB} *perpendicular to the mandible base, acting in the cranial direction, retains the constant value on the regions without loading, but in the loading zone it changes the action direction. The forces acting to fosse articulates are of unequal intensities and they are higher in the balances joint. There is an explicit asymmetry of moment* M_{fN} *between the left and right side of the jaw, both in side and action direction. The jaw torsion moment retains approximately the same values on the working side, while on the balance side it changes the action direction, by which that change is performed in short region. Moment* M_{fB} *is nearly symmetrically distributed in relation to the medial jaw plane.*

Key words: *Forces, moments, lower jaw*

Introduction

In order to make the mastication function (cutting, tearing, crumbling or milling of food) possible, it is necessary to make definite pressure to food by the teeth. However, the teeth represent only, more or less, the passive elements, which indirectly, through the bone into which they are fixed or through the denture if artificial teeth are in question, are moved by action of the respective muscles. As the upper jaw is fixed for the osseous skull massive, it is thought that it is immovable, and the lower is movable one. In forming mastication forces the grater number of muscles take place, the position and direction of which are mutually differed, but yet there are two symmetrical groups, left and right one.

The forces forming predominantly during mastication function act to the jaw bones in different directions in dependence on acting of muscles that do definite action.

The first data about spreading directions of forces within jaws were noted in 1884 by Wolf.

Many authors, both anatomists and dentist did the anatomy styding of the orofacial system. However, thought biomechanical considerations of occurrences in osseous structures of orofacial system during its function were interesting for prosthodontist, enough attention was not paid to this problem, both in domestic and foreign literature available to us.

There are enough data about mastication force value, both with natural and artificial teeth. These data are very heterogeneous and are not mutually comparable enough because the measuring methodologies among researches are different.

So far, there are very few investigations of teeth force moments, though their importance has been emphasized by more authors (1,2,3). On the first, more analytical studies of masticatory system, was performed in 1987 by Otten, but it was done on nice jaws. Koolstra (4) has tested by biomechanical analysis of mathematical model of the lower jaw the hypothesis that muscle forces and movements of mandible conditions by articulate surfaces are necessary and enough condition for generating simple movements of jaw closure. He has established that the normal movement, including the sliding movement of condyles along the articulate convexity, may be generated by various separated pairs of mastication muscles, among which the various parts of masseter muscles and medial pterygoid muscles seem to be able to realize this action. The muscle orientation in relation to the jaws and their force moments with normal and long face patients was investigated by Spronsen (5). He concludes that there is small difference in spatial orientation of the jaw muscles with long and normal-face persons and that it does not considerably confirms assertions about the various levels of the molar bite force among these persons. Hart et al.

conclude that the stress analysis of condylar added piece by method of final elements may establish precise relationships, but must be confirms by forces and stresses measured by controlled experiment (6). For the loading testing of the jaw joint Hatcher (7) has developed two models: mechanical, on the basis of human skull, and mathematical, obtained by the vector analysis combined with measurements undertaken from the mechanical model. Santos (8) has performed the vector analysis of forces on the mechanic model of mandible based on the static equilibrium at ten various mandible positions. Semenikov and Tjomanok (9) have applied the mechanically-mathematics testing method of forces and stress in the lower jaw at physiological loading. They observed the lower jaw as a plane carrier by which the mathematics-mechanical analysis is simplified according to Throckomorton (10) the precise relationship between stress and forces in human condyle remains unknown so far.

According to Eckerman's "Gnathodynamic law" the occlusal force is inversely proportional to the distance from the jaw joint (11).

Mansour quotes that the relationship between force and distance from condyles on both jaw sides is linearly decreasing and nonhyperbolic function. In other words, the force is directly proportional to the distance from condyles with a negative slope (11).

The objective of this study is to establish forces distribution and their moments in some parts of the toothless mandible at stimulation of one sides ridge loading in the lateral teeth region.

Material and Methods

The chosen method of researching is a combination of clinical and analytical (mechanically-mathematics) problem solving procedure.

The clinical part represents bite force measurement in persons with total dentures in both jaws. For this part were used patients from clinical practice, of both sexes, with correct dentures, without subjective complaints, of age structure 31-85 years. There were 120 persons at all (60 female and 60 male). Bite force was measured by mechanical gnathodynamometter in the region of the second premolar and first molar on both jaw sides. All measurements were done at least a month after prosthesis delivery. The obtained results were statistically treated. The average value of the obtained bite force was used as one of the parameters for the second part of investigations.

In the second part of investigations mandible was considered as class II lever.

The analytical part comprised forces and moments calculation in some regions of teethless lower jaw under average force loading obtained in the first testing part. For mathematical model of mandible the anatomic data for toothless jaw used in previous investigations (12) were used.

It was done one-side loading, that is, mastication was simulated on the right jaw side in the region of the second premolar and first molar. The applied force was 126,40N.

Moments and forces were calculated in mandible body only.

Lower jaw geometry

The lower jaw (picture 1) has a form of a second order parabola the equation of which in Fig. 1.

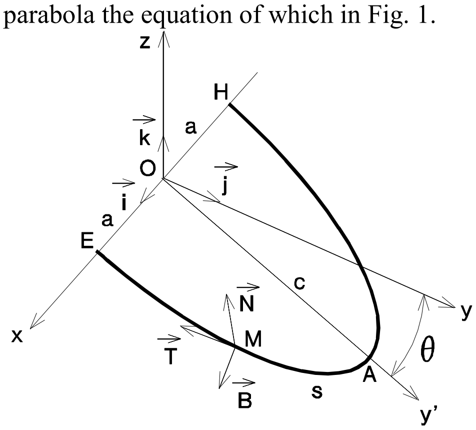


Fig. 1.

coordinate system Oxy' reads:

$$y' = c\left(1 - \frac{x^2}{a^2}\right) \tag{1}$$

where $c = \overline{OA}$ jaw "arrow", and $2a = \overline{HE}$ jaw width.

Let us notice on the jaw an optional point M(x,y'). Arch length s = AM is obtained from expression:

$$s = s(x) = \frac{1}{2a^2}\left[x\sqrt{a^4 + 4c^2x^2} + \frac{a^4}{4c}\ln\frac{2cx + \sqrt{a^4 + 4c^2x^2}}{a^2}\right]. \tag{2}$$

In relation to horizontal Oxy plane jaw was sloped for angle θ, and the following relationships between jaw coordinate axis y' and coordinates y and z in coordinate system Oxyz can be established: $y = y'\cos\theta$, $z = -y'\sin\theta$.

Let us suppose that from the relation (2) x = x(s) can be determined by inversion, then coordinate points M may be given in the function of jaw arch s length.

Let us set in point M the natural co-ordinate system: tangent, main normal, binormal, the unit vectors of which are $\vec{T}, \vec{N}, \vec{B}$. These vectors can be expressed through unit vectors $\vec{i}, \vec{j}, \vec{k}$ of Decart coordinate system Oxyz. The unit vector $\vec{T}$ reads:

$$\vec{T} = \frac{1}{\sqrt{a^4 + 4c^2x^2}}\left(a^2\,\vec{i} - 2cx\cos\theta\,\vec{j} + 2cx\sin\theta\,\vec{k}\right), \tag{3}$$

while the unit vector of main normal $\vec{N}$ is:

$$\vec{N} = \frac{1}{\sqrt{a^4 + 4c^2x^2}}\left(-2cx\,\vec{i} - a^2\cos\theta\,\vec{j} + a^2\sin\theta\,\vec{k}\right) \tag{4}$$

The unit vector of binormal $\vec{B}$ reads:

$$\vec{B} = -\sin\theta\,\vec{j} - \cos\theta\,\vec{k} \tag{5}$$

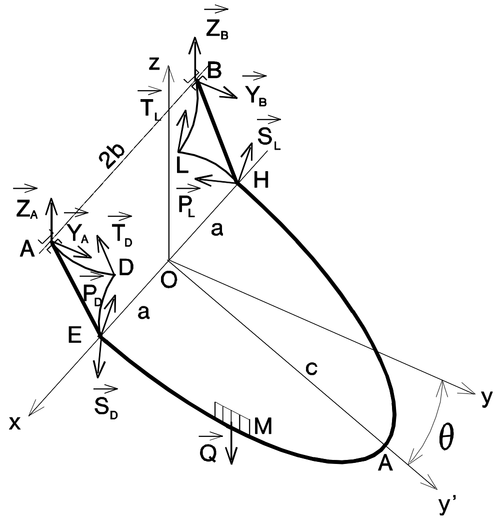


Fig. 2.

Outside and inside loadings of the lower jaw

The support of the lover jaw was in both fosse articulates in points A and B. It was fixed by three pairs of muscles (masseter-S, pterygoideus medialis-P and temporal-T) percentagely distributed, according to muscle transversal cut, and spaciously in accordance with their anatomical position on both jaw sides. Two muscle pairs each were bound in points E and H, and one pair in points D and L.

The supports, that is the jaw joints, in points A and B may be considered as cylindrical ones because they do not hinder the jaw movement in Ox direction. By mastication muscle contraction the equally divided loading will continually act to the lower jaw, by which Q is total force of this loading. On the basis of experimental data it is known that relationship of forces in muscles which are joined at one side of jaw is:

$$S : P : T = 1{,}875 : 1 : 2 \tag{6}$$

For the system formed of outside forces, the balance conditions read (System of Eq. 7).

In relation (7) marks ($\alpha_P,\beta_P,\gamma_P$), ($\alpha_S,\beta_S,\gamma_S$), ($\alpha_T,\beta_T,\gamma_T$) are introduced - angles which forces ... (P_L,P_D) (S_L,S_D) (T_L,T_D) make with coordinate axes x,y,z ($\pm b,-y_0,z_0$) are coordinates of points A and B, ($\pm x_1$, y_1,z_1) are coordinates of points D and L, $t_x = y_1\cos\gamma_T + z_1\cos\beta_T$, $t_y = z_1\cos\alpha_T - x_1\cos\gamma_T$, $t_z = x_1\cos\beta_T + y_1\cos\alpha_T$

$$\begin{gathered}
(T_D - T_L)\cos\alpha_T - (P_D - P_L)\cos\alpha_P + \\
+ (S_D - S_L)\cos\alpha_S = 0, \\
Y_A + Y_B - (T_D + T_L)\cos\beta_T - (P_D + P_L)\cos\beta_P + \\
+ (S_D + S_L)\cos\beta_S = 0, \\
Z_A + Z_B + (T_D + T_L)\cos\gamma_T - (P_D + P_L)\cos\gamma_P + \\
+ (S_D + S_L)\cos\gamma_S - Q = 0, \\
-(Z_A + Z_B)y_o - (Y_A + Y_B)z_o + (T_D + T_L)t_x - \\
- Qy'_T\cos\theta = 0, \\
-(Z_A - Z_B)b + (T_D - T_L)t_y - (P_D - P_L)a\cos\gamma_P - \\
- (S_D - S_L)a\cos\gamma_S + Qx_T = 0, \\
-(Y_A - Y_B)b - (T_D - T_L)t_z - (P_D - P_L)a\cos\beta_P + \\
+ (S_D - S_L)a\cos\beta_S = 0.
\end{gathered} \tag{7}$$

From the first equation of system (7) and relation (6) it follows:

$$\begin{gathered}
P_D = P_L = P, \\
T_D = T_L = T = 2P, \\
S_D = S_L = S = 1{,}875\,P.
\end{gathered} \tag{8}$$

Solving the rest equations of system (7) it is obtained (System of Equation 9).

Determination of inside loading in the lower jaw is interesting for dentists. Let us suppose that mandible is cut in some cut-point p-p. By parallel moving of all forces from the left or right side into cut-point p-p, the main vector $\overrightarrow{F_{Rp-p}}$, which is numerically equal to geometric sum of forces of one side of cut-point p-p and the main moment $\overrightarrow{M_{p-p}}$, which is numerically equal to geometric sum of moments of al one side of cut-point p-p, are obtained.

Axial force in the lower jaw represents the projection of the main vector to tangent:

$$\begin{aligned}
F_{aks} &= \overrightarrow{F_{Rp-p}} * \vec{T} = \\
&= \frac{1}{\sqrt{a^4 + 4c^2x^2}}[a^2X_R - (2cx\cos\theta)Y_R + (2cx\sin\theta)Z_R],
\end{aligned} \tag{10}$$

where star (*) denotes scalar product, and X_R, Y_R and Z_R are projections of the main vector to axes x, y and z.

Transversal force in the lower jaw has two components that are obtained by projecting the main vector to directions of the main normal and binormal.

$$\begin{aligned}
P &= \frac{1}{2}Q\frac{y_o + y'_T\cos\theta}{2t_x + y_o(2\cos\gamma_T + \cos\gamma_P + 1{,}875\cos\gamma_S) - z_o(2\cos\beta_T + \cos\beta_P - 1{,}875\cos\beta_S)}, \\
Y_A &= Y_B = \frac{1}{2}Q\frac{(2\cos\gamma_T + \cos\gamma_P + 1{,}875\cos\gamma_S)(y_o + y'_T\cos\theta)}{2t_x + y_o(2\cos\gamma_T + \cos\gamma_P + 1{,}875\cos\gamma_S) - z_o(2\cos\beta_T + \cos\beta_P - 1{,}875\cos\beta_S)}, \\
Z_A &= \frac{Q}{2}\left[1 + \frac{x_T}{b} - \frac{(2\cos\gamma_T + \cos\gamma_P + 1{,}875\cos\gamma_S)(y_o + y'_T\cos\theta)}{2t_x + y_o(2\cos\gamma_T + \cos\gamma_P + 1{,}875\cos\gamma_S) - z_o(2\cos\beta_T + \cos\beta_P - 1{,}875\cos\beta_S)}\right], \\
Z_B &= \frac{Q}{2}\left[1 - \frac{x_T}{b} - \frac{(2\cos\gamma_T + \cos\gamma_P + 1{,}875\cos\gamma_S)(y_o + y'_T\cos\theta)}{2t_x + y_o(2\cos\gamma_T + \cos\gamma_P + 1{,}875\cos\gamma_S) - z_o(2\cos\beta_T + \cos\beta_P - 1{,}875\cos\beta_S)}\right],
\end{aligned} \tag{9}$$

$$F_{tN} = \overrightarrow{F_{Rp-p}} * \vec{N} = = \frac{1}{\sqrt{a^4+4c^2x^2}}[-2cx\,X_R-(a^2\cos\theta)Y_R+(a^2\sin\theta)Z_R], \quad (11)$$

$$F_{tB} = \overrightarrow{F_{Rp-p}} * \vec{B} = -(Y_R\sin\theta+Z_R\cos\theta). \quad (12)$$

Torsion moment of the lower jaw represents projection of the main moment to tangent direction:

$$M_{tor} = \overrightarrow{M_{p-p}} * \vec{T} = = \frac{1}{\sqrt{a^4+4c^2x^2}}[a^2M_x-(2cx\cos\theta)M_y+(2cx\sin\theta)M_z], \quad (13)$$

where M_x,M_y and M_z are projections of the main moment to axes x, y and z.

Torsion moment of mandible has two components that are obtained by projecting the main moment to direction of the main normal and binormal:

$$M_{fN} = \overrightarrow{M_{p-p}} * \vec{N} = = \frac{1}{\sqrt{a^4+4c^2x^2}}[-2cx\,M_x-(a^2\cos\theta)M_y+(a^2\sin\theta)M_z], \quad (14)$$

$$M_{fB} = \overrightarrow{M_{p-p}} * \vec{B} = -(M_y\sin\theta+M_z\cos\theta). \quad (15)$$

On the basis of analytical expression (10)-(15) they inside loadings of mandible in every its cut may be shown.

Numerical results

By determination of forces and moments in a jaw, the following geometric data were used:

$a = 28.5$ mm, $c = 60$ mm, $b = 49$ mm, $\theta = 22^o$,

$x_1 = 41$ mm, $y_1 = 12$ mm, $z_1 = 40$ mm,

$y_o = 21$ mm, $z_o = 43$ mm.

Angles that determine muscle position are:

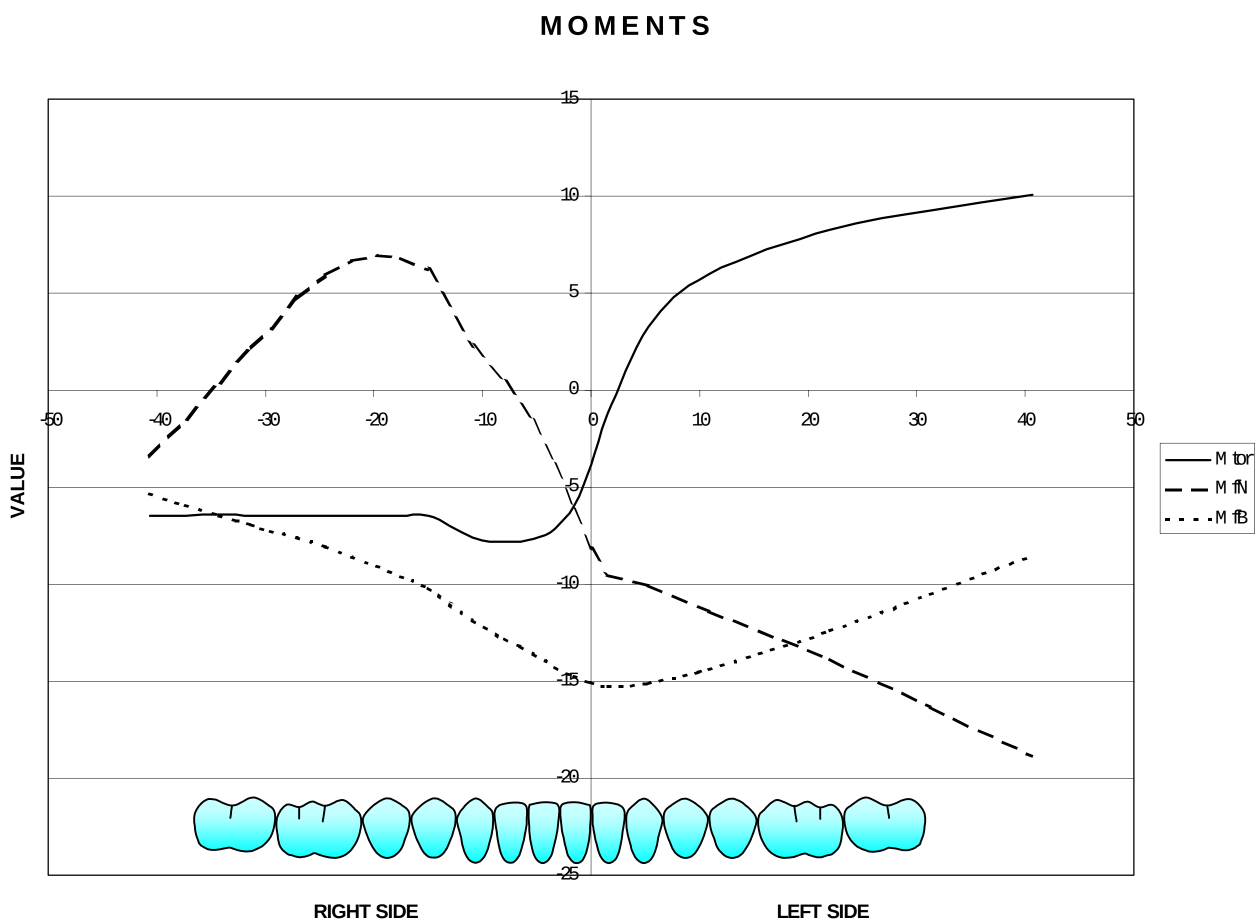
$\alpha_T = 64^o$, $\beta_T = 80^o$, $\gamma_T = 28^o$,

$\alpha_P = 69^o$, $\beta_P = 61^o$, $\gamma_P = 37^o$,

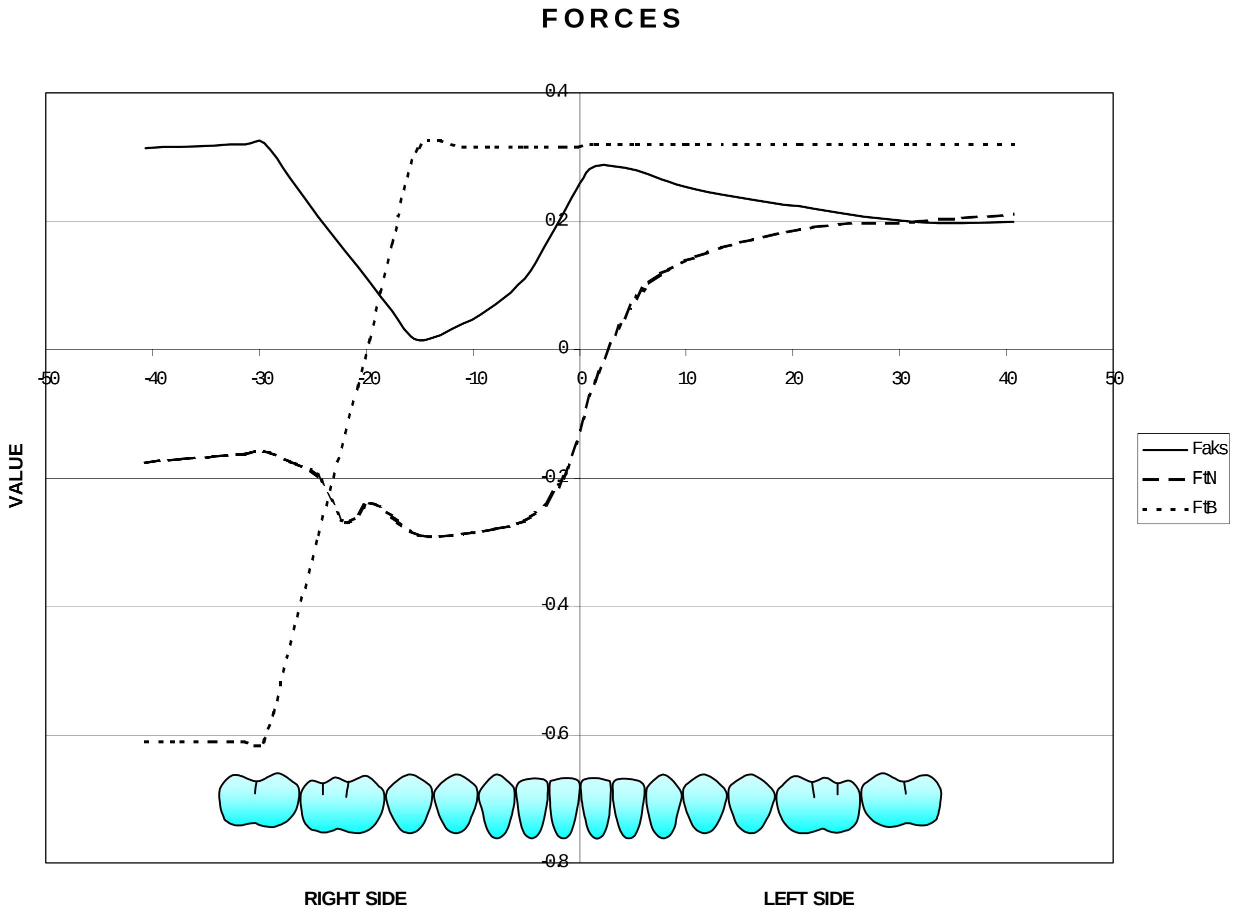
$\alpha_S = 73^o$, $\beta_S = 64^o$, $\gamma_S = 32^o$.

The average bite force is $Q = 126{,}4$ N. Attaching point of force Q is: $x_T = 15.6$ mm, $y'_T = 42$ mm.

Results show that moment M_{fN} leads to torsion of a jaw caudal at the working side. Bending intensity is the highest in the first molar and second premolar region, but going toward the middle of a jaw it decreases, so that at the left side it would come to torsion appearance towards cranial, that is, opposite of the right side and with the highest value in the second molar region. The least value of this moment by absolute value is in the second and third tooth location region, right from medial line. Moment M_{fB} falls in direction of jaw base normal giving rotation both the left and right jaw side in



Graph 1.



Graph. 2.

counter clock-wise direction, but its highest value is in protuberance mental region and going distally its value decreases. M_{tor} rotates mandible body of the right side viewed from distal side in counter clock-wise direction. The left mandible body side viewed from the same side rotates in clock-wise direction, but intensity of rotation at the left side is somewhat higher by absolute value. The least moment of torsion is located about the middle of a jaw, left from medial line.

The highest value of force F_{tN} for the right jaw side, acting in bucal direction, is in the first premolar, eye-tooth and lateral incisor region, so that going toward the left jaw side its value would begging to decrease, and its least absolute value between central and lateral incisor, wherefrom the force acting direction changes (so it acts now toward lingual) and intensity gradually increases, so that its maximal absolute value be in the second molar region.

Force F_{tB} is the highest in the second molar region on the right side and acts in cranial direction, so that in the first molar and second premolar region its value would rapidly decrease and in the first premolar region change acting direction, and retain that intensity to the second molar region of the left side.

Force F_{aks}, acting along mandible body axis going from left to right side, has the highest intensity in the second molar region, wherefrom it begins rapidly to increase and reaches its minimal value (near zero) in foramen mental region, so that going toward medial plane its value would again rapidly increase to approximately initial value, going therefrom toward the left half of a jaw its intensity decreases mildly.

Forces in head of condyloid process of mandible in cranial direction are higher by intensity in relation to other directions. They differ also mutually, so that force in the joint at the balance side is higher in relation to the working side and they are of order of forces value in muscles.

Discussion

In desire to understand essence of happenings in human bones during their function, as well as in jaw bones, the grater number of authors was studying by various methods the phenomena and reactions present in bones.

Methods for stress research (method of photoelasticity, brittle lacquers, tensiometry, holographic interferometry, mathematics analysis etc.) do not exclude but mutually supplement each other, giving more complete acknowledgement of happenings studied. Calculation of moments and forces in some structures, so as in some portions of a jaw, today is possible exclusively by method of theoretical mechanics. Some studies for this problem examination were based on two-dimensional models (in sagital direction), and some ones consider this problem through three-dimensional models.

According to Semenikov and Tjomanok (9) findings, transversal forces have the highest values in the jaw body region, and then in a jaw branch they change their direction, while in condyle their intensity decreases. Longitudinal forces have the highest level in the joint prolongation. Forces and moments have the highest value in angle part of mandible, so that their value in the joint would be zero.

Own researches on the lower jaw model in the form of spatial carrier which is not symmetrically loaded, lead to more complicated expressions of mechanical values, but they are much closed to the real state and give thorough picture about inside bone loadings. The results obtained for forces and moments in this study represent generalization of results obtained by Semenikov and Tjomanok (9), because the problem was here analyzed three-dimensionally. However, agreements in diagrams obtained for forces and moments in definite jaw cuts may be noticed.

Watt (13), Simon (14), McNamara (15) and Hinton (16) agree that forms of mandibular condyle and other parts of the jaw joint depend on the functional loading level.

According with researches by Santos (8) the lateral slope of cusp of the teeth and condyle path slope have considerable influence to forces which act in joints and teeth.

Results obtained by Koolstra (4) are in contrary to general opinion that muscles with force component directed forward can't be suitable for realization of jaw moments by which condyle is moving backwards. This can be explained by biomechanical analysis which includes not only muscles and forces in the joint that were used in the standard anatomy books, but also torques generated by those forces.

The balance jaw joint, according to findings performed on mathematical model by Ferrario (17), is not always more loaded than the working one, what is the case also in these researches. Differences existing are due to loading way of both models.

Acting directions of moments M_{tor} of the left and right jaw side confirm the fact that the action of mastication muscle is uneven from outside and inside mandible side by relations of transversal cuts of the same, so it comes to rotation of the left and right side mandible body toward medial line.

Comparing mechanical and mathematical model for research of the jaw joint loading, Hatcher (7) came to the conclusion that variations of both models are sometimes considerably different. He explains them by consideration of experimental errors bound for muscle forces measurements. Comparisons of these models show, however, the similar trends in all cases. The same author, on the basis of his researches of the jaw joint mechanics by comparison of results of mechanical and mathematical model, concludes that both models mutually supplement and represent a progress in relation to the previous working ways.

The attempt of absolute "copying" of conditions of forces and movements acting in bones during their function is difficult to be realized, so the results obtained are of approximate character, but still acceptable, useful and applicable in practice.

Conclusion

The results obtained point out to the following conclusion:

1. Forces are unevenly distributed along the jaw body on the left and right side, by which they are of the higher intensity at the loading acting side. Force F_{tB} perpendicular to mandible base, acting in cranial direction retains the constant value in region without loading, but in the loading zone it changes acting direction.
2. Forces acting to fosse articulate are of uneven intensities and are higher in the balance joint.
3. There is explicit asymmetry of moment M_{fN} between the left and right jaw side both in size and acting direction. Jaw twisting moment retains approximately the same values at the working side, while at the balance side it changes acting direction, by which that change takes place in short space. Moment M_{fB} is nearly symmetrically distributed in relation to the jaw medial plane.

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BIOMEHANIČKA ANALIZA SILA I MOMENATA GENERISANIH U MANDIBULI

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Kratak sadržaj: *Sile koje se formiraju u toku funkcije žvakanja deluju na vilične kosti u različitim pravcima u zavisnosti od delovanja mišića koji vrše odredjenu akciju. Cilj ove studije je da utvrdi distribuciju sila i njihovih momenata u pojedinim delovima bezube mandibule pri simulaciji jednostranog opterećenja grebena u predelu bočnih zuba. Izabrani metod istraživanja je kombinacija kliničkog i analitičkog (mehaničko-matematičkog) dela. Dobijeni rezultati pokazuju da su sile neravnomerno raspodeljene duž tela vilice sa leve i desne strane, pri čemu su većeg intenziteta na strani gde dejstvuje opterećenje. Sila* F_{tB} *upravna na bazu mandibule, koja deluje u kranijalnom pravcu, zadržava konstantnu vrednost na delovima gde nema opterećenja, a u zoni opterećenja menja smer dejstva. Sile koje deluju na fossu articularis su nejednakih intenziteta i veće su u balansnom zglobu. Postoji izražena asimetrija momenta* M_{fN} *između leve i desne strane vilice, kako po veličini tako i po smeru dejstva. Moment uvijanja vilice zadržava približno iste vrednosti na radnoj strani, dok na balansnoj strani menja smer dejstva, pri čemu se ta promena odvija na kratkom prostoru. Moment* M_{fB} *je skoro simetrično raspodeljen u odnosu na medijalnu ravan vilice.*

Ključne reči: *Sile, momenti, donja vilica*

The predicted deformations and forces in the extensor tendon network broadly agree with the results obtained by previous experimental in vitro studies. As well as estimating the forces generated by each tendon component, the proposed method can also be used to calculate the bone-to-bone contact forces at each finger joint. Thus, it can be used to provide comprehensive biomechanical data for in vivo loading of the musculoskeletal complex of the human finger. Analysis of these activities indicates that joint forces in excess of 100 N may be common at the metacarpophalangeal joint (MCP) due to carrying objects such as groceries or while opening jars. The model predicted that stresses in excess of 2 MPa, similar to stresses at the hip, occur at the MCP with the properties of cancellous bone playing a significant role in the magnitude and distribution of stress.Â The problem of modelling stresses incurred at the finger joints is critical to the design of durable joint replacements in the hand. The goal of this study was to characterise the forces and stresses at the finger and thumb joints occurring during activities such as typing at a keyboard, playing piano, gripping a pen, carrying a weight and opening a jar.