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The simulation of mastication efficiency of the mucous-borne complete dentures

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ABSTRACT

Purpose: The aim of this study was to present rules for numerical investigations of mastication efficiency of mucous-borne complete dentures.

Design/methodology/approach: Finite element method (FEM) large displacements analysis with denture detaching and sliding at mucous membrane interface was employed. The possibility of a lower denture destabilization under oblique mastication load was modeled. Denture stabilization at balancing contact „at time" and „delayed" was modeled with increasing of a distance to the opposite denture. An unfavorable mucous membrane foundation was assumed.

Findings: Pressures beneath dentures during stable vertical occlusal loadings are lower than pain threshold of mucous membrane even when the denture foundation was very unfavorable. Simulation of realistic oblique mastication force results in a denture destabilization. Denture experienced a large slide, completely lost adherence at balancing side and the balancing contact was needed to achieve stabilization. The pressures beneath denture under oblique load increased to values much higher than pain threshold and the „delayed" balancing contact influenced additional increase of pressure values.

Research limitations/implications: In the FEM study only characteristic unfavorable denture foundation and conventional denture type were analyzed.

Practical implications: Defined values of pressure beneath dentures show that it is necessary to underlay the dentures. The influence of „delayed" balancing contact on significant increase of stress beneath dentures indicates that in case of a problem with stabilization of dentures it is necessary to introduce stabilization on the implants.

Originality/value: Universal rules of conducting a numerical experiment and interpreting its results constitute the base and encouragement to complete further practical tasks awaiting engineers and prosthetists.

Keywords: Denture material; Finite Element Method (FEM); Mastication force; Comfort; Soft tissue pain

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

A denture is a technical creation and it is defined as a mechanical device, the purpose of which is to restore oral functions lost as a result of toothlessness [1]. In the process of treating complete toothlessness the most economical dentures - mucous-borne or settling dentures - are most commonly used [2], due to the use of the support on the mucosa of the denture foundation. Development and improvement of the materials, production technologies and registration methods of balancing contacts, which lasted almost a century, unfortunately only to a small degree influenced the increase of success in treatment using settling dentures. The main reason for these failures is the deficiency of functional features, determined by functional insufficiency, which is defined as a sum of biological, technical and material factors of the system. Functional insufficiency of settling dentures becomes a reason for severe difficulties in professional and personal life. Problems with comminution of food (insufficiency of mastication) impedes everyday life and social interactions, while poor maintenance of dentures on the foundation (poor retention and stabilization) in the course of speech and facial expressions eliminate people from social life and professional activity. Frequently as a result of discomfort a complete failure of treatment occurs, which leads to the use of dentures exclusively for aesthetic reasons.

In the case of material design of the most popular settling dentures we come across the most severe obstacle. Thematic literature is abound with the attempts to assess functional features of materials and dentures, however it is difficult to formulate any general conclusions regarding denture design on its basis. In the case of the lack of knowledge in regards to the influence of the system features on its behavior, we are left with statistical and observational research which indicates correlation dependencies, but no cause-and-effect relationships. In the case of living systems usually the only tools to gain knowledge essential to solve material and construction problems are simulation studies by Finite Element Method (FEM) [3,4]. FEM allows to define the distribution of the sought value of physical quantity inside the system structures and the effect assessment of introducing material changes, when the degree of complexity makes it impossible to conduct analytical calculations, while conducting measuring tests is impeded or impossible.

Over 80% of people using dentures suffer from pain due to overload of soft tissue under dentures [5,6]. As a result of mechanical interaction of dentures, mucous membrane injuries occur; their frequency reaches a significant level of 15-20% [7] Stomatopathy of mucous membrane is difficult to heal and itssymptoms include inflammation and fungal infections, which mostly are the results of mechanical overloads [1,8,9]. Therefore the threshold of mucous membrane pain sensitivity to pressure should be distinguished as the most important property of mucous membrane surface [10,11], which covers lateral segments of the mandibular alveolar bone. The assessment of pain sensitivity to pressure is conducted on the basis of complete immediate deflection (immersion of the penetrator), which corresponds to realization of defined force value without the differentiation of flexible and viscous feature share in deformation. Complete immediate deflection constitutes relatively most comfortable measuring feature of mucous membrane which to a significant degree depends on the thickness of the mucous membrane and it flexibility. Immersion of the penetrator corresponds to resilience of the mucous membrane. In prosthetics through resilience we characterize the mucous membrane ability for elastic deformations with which the ability to move overloads is connected. Low resilience is commonly recognized as the main factor contributing to the failure of treatment with settling dentures [12]. In the conditions of a prosthetic office only palpation assessment of resilience and descriptive categorization of mucous membrane are applied. In FEM practical calculations the characteristics of mucous membrane are brought closer by the flexibility module calculated on the basis of compression tests.

In Fig. 1 threshold values of pain sensitivity for pressure, obtained in studies, were presented [10,11] on the basis of tests performed with a cylindrical penetrator. The values provided in units of mass in the papers [10,11] were calculated into units of pressure through dividing the values of force by known penetrator surface, which provides nominal values of pressure. Threshold of pain sensitivity is a strongly individual property. The average threshold of pain sensitivity in the area of premolars (from A to P1), which carry the largest occlusal forces, is approximately 630 kPa. Sensations of pain can occur for the value of approximately 300 kPa, but also for 1500 kPa. Similar values of average pain threshold 686-1372 kPa were provided by the source [13].

Simulation studies of the conditions of living systems functioning require application of model simplified assumptions, without which it is not possible to perform numerical experiments and obtain any answers. The level of compliance with the results of measurements on physical models, and most of all with clinical observations or measurement data from living systems, decides about the correctness of models and the possibility to use them. Functioning of settling dentures is connected with significant displacements (movements) of dentures in relation to the surface, which accompany chewing and other activities within the oral cavity. In the phase of food mastication the displacements are limited by the opposite denture on the side which is not working on the so called balancing contact. Functioning of balancing contacts turns out to be a necessary condition to achieve denture stabilization on the surface and masticatory efficiency [14-16]. In the mechanical sense, balancing contact, which balances the destabilizing effect of forces on the working side, is also a force and it should be called an occlusal balancing overload or occlusal balancing force. Due to the terminology accepted many years ago, resulting from a more kinematic approach to biostatics of dentures as to its mobility, in this paper the notion of "balancing contact" has not been changed. The value of denture displacements during food mastication obtained in this paper [16] through direct measurement within the oral cavity was presented in Fig. 2. If the dentures were not tailored to the surface [17], an increase of displacement range is stated in this paper, as presented in Fig. 3.

The range of dentures displacements affects the overloads of the mucous membrane. Therefore, simulation studies, in which contact phenomenon of contact slide and denture detachment from the surface are not imitated, provide comparisons of different types of dentures in significantly simplified conditions [3,4]. As it was recently proven that there is a possibility to conduct FEM large displacements analysis for dentures [18-20].

The purpose of this paper is to present methodological bases of FEM simulation of mastication efficiency of mucous-borne dentures. The null hypothesis was that finite element method analysis of mastication load transfer allows for the estimation of mastication efficiency of lower complete dentures in realistic conditions with sliding and detaching on the mucous membrane surface. A lot of attention was paid to assess the compliance of FEM calculations with the results of laboratory tests and clinical observations.

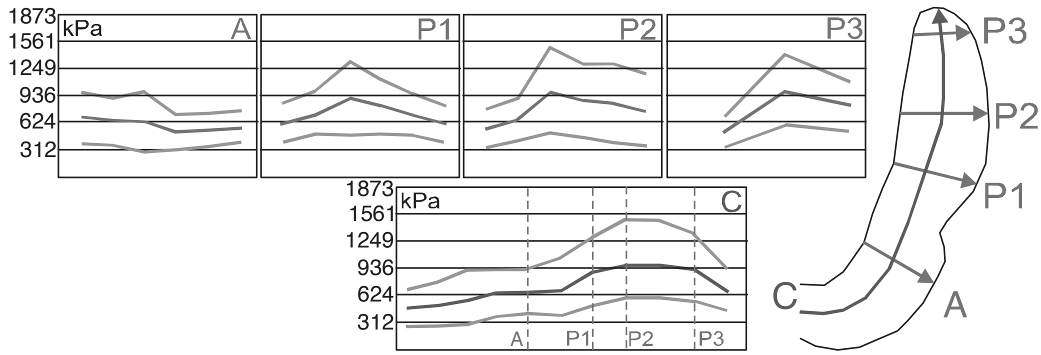

Fig. 1. Threshold value profiles of pain sensitivity for pressures of mucous membrane of the lower denture foundation (the range of values and averages) along the marked paths (ranked by work [11])

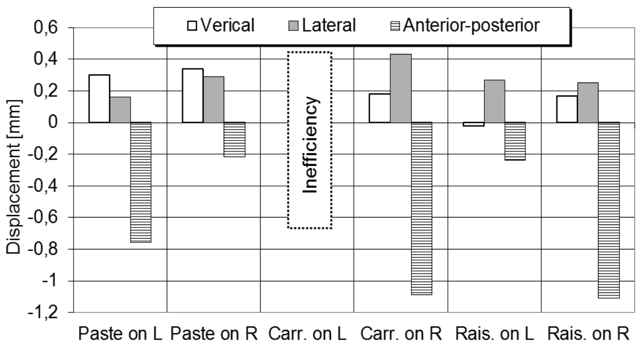

Fig. 2. The displacements of the balancing side during the mastication on the left side (L) or the right side (R) of food of different consistencies: fish paste, carrot or raisins [16]

2. Methods

2.1. FEM model of denture and prosthetic foundation

Individual biological features of denture foundation condition functional efficiency of the dentures. The problem with the lack of functional efficiency and failure in treatment intensify especially in the case of detrimental conditions of the lower denture foundation. Features of toothless alveolar shape, which promote overload effects of mucous membrane, are listed as features which impede treatment due to discomfort caused by pain. Most of all we shall list [1] atrophied shapes of toothless alveolar with sharp crest, so called „knife-edged". Unfavorable conditions of denture foundation has a significant position in the papers of prosthetists. In the case of mandible the „knife-edged" shapes occur in 75% in the anterior segment and in 38% in the area of premolars [21]. The geometry of denture foundation was assumed based on the average plaster models reflecting characteristic "knife-edged" foundations. A segment of the mandibular alveolar process that constitutes the denture foundation was represented in the model - Fig. 4. In the study the methodology for creating numerical models (CAD) from medical imaging as computer tomography (CT) and magnetic resonance (MRI) was discarded. The CAD from CT requires identification of typical cases and exposing the organisms to harmful radiation. The typical engineering CAD software (Autodesk Inventor^{TM}) was used to design the models of foundation and dentures.

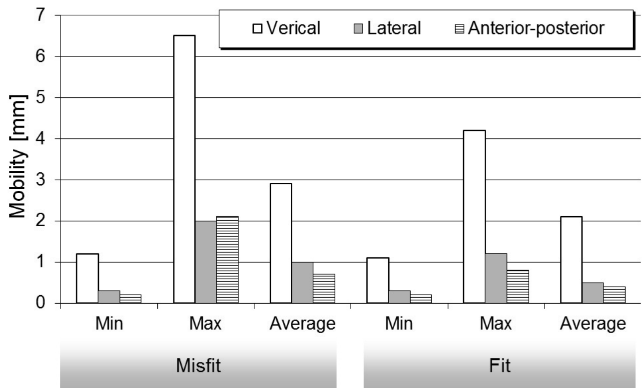

Fig. 3. Mobility (displacements) of the dentures in the case of good or bad tailoring relative to the surface [17]

Denture tooth irregular shapes were neglected, because this unnecessarily increases the element number outside the interest zone and time of the simulation. The model was exported to FEM software (Ansys^{TM}). Finite element discretization of an anatomical free uneven surfaces results in non-unique representation of a normal between the contact surfaces [22] when automatically generated tetrahedral finite elements are used. In such cases, the higher mesh density does not improve the results, but it increases inequality of stresses, as the values of stress grow around unfavorably oriented contact elements. The reason for this is the lack of orientation control of the normals when the mesh is automatically generated. An effective method to eliminate inequalities of stress patterns is the application of a coherent mesh at the contact surface, if initial contact surfaces are known. Then, special preparation and trim of contact surfaces in the CAD software is possible. If the two contacting surfaces have the same geometry, then the coherent mesh generation is possible. In the model, the contact zone was divided with linear hexahedral 8-node elements (ANSYS^{TM} “185-brick”) that take a reasonable amount of computation time. The contact stiffness matrix was updated in each equilibrium Newton-Raphson iteration with contact detection at Gauss points.

Bone was omitted in calculations and the model was fixed at the bone interface. The assumption is justified by high bone stiffness related to significantly higher modulus of elasticity of bone tissue in comparison with soft tissue. Mandibular bone deformations were tested in the pilot study and can be neglected because of an incomparably larger denture displacement on the soft mucous membrane foundation in comparison with mandibular bone strains.

Modulus of elasticity of E=17 GPa for the cortical bone was assumed; whereas for the spongy bone E=600 MPa; at the Poisson ratio in both cases equal ν=0,3. Linearly elastic mechanical characteristics were assumed in order to simplify the contact calculation in the model. The unfavorable "hard" mucous membrane was analyzed through the adoption of extremely thin 0,5 mm soft tissue layer and assumed extreme Young modulus value of 5 MPa. The incompressibility was, to some extent, represented by the high Poisson ratio ν = 0,49. The denture saddles and tooth material were described with E = 2000 MPa and ν = 0,3.

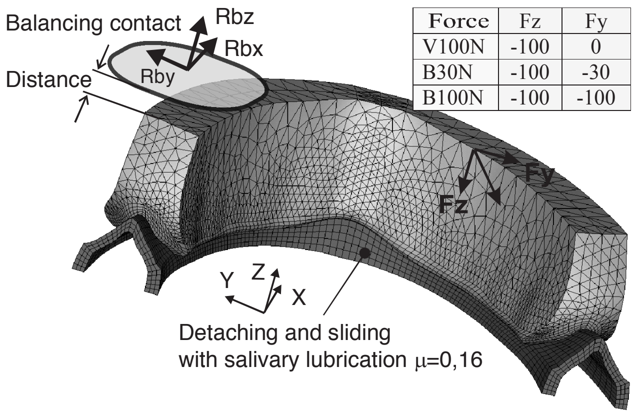

Fig. 4. The model of the lower denture on the atrophied foundation with occlusal loads

Table 1.
Selection of simulated operational load conditions and mastication efficiency assessment criteria

Mastication	Occlusal forces: » Vertical V100 N » Oblique B30 N » Oblique B100 N
	Stabilization on balancing contact: » with the distance of 0,1-1,0 mm » with or without slide
Assessment criteria of mastication efficiency	- Normal and tangential contact stresses σ_N together with slide value P on the surface of the mucous membrane (friction work W_T) - Denture displacements U - Reaction force on balancing contact R

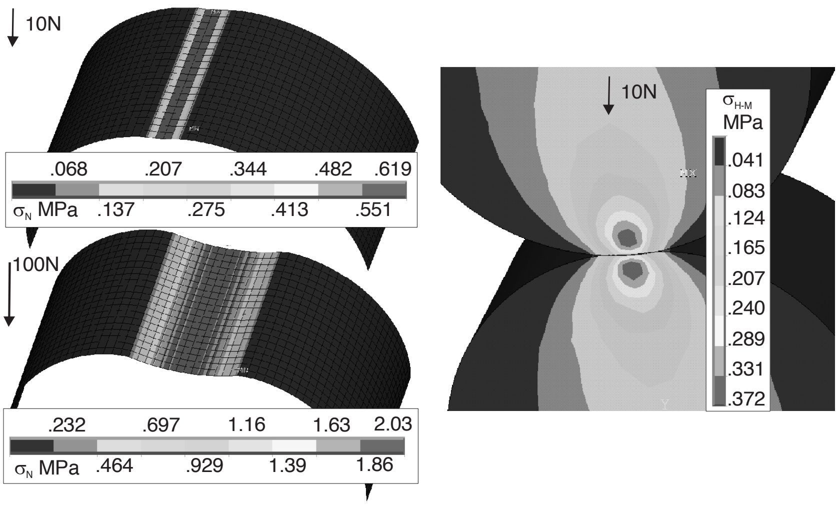

Fig. 5. The distribution of contact stresses and substitute stresses H-M between cylinders with the ratio of flexibility modules of 2000/5 at a load of 10 N or 100 N (mesh size "M0.5")

2.2. A model of denture destabilization on foundation and stabilization on a balancing contacts during mastication load transfer

Nonlinear large displacements FEM analysis with the possibility of denture detaching and sliding on the interface of the mucous membrane was employed. The denture and mucous membrane were considered as deformable bodies. The augmented multiplier Lagrangian method with an implemented classical linear friction model was employed for calculations of contact at the mucous membrane interface. The friction coefficient was assumed to be approximately 0.16. The lost denture adherence to the foundation was assumed when there are no negative interfacial normal stresses. The low adhesive forces omitted in the contact calculation play a secondary role during transfer of high mastication load.

In model studies a change of the equilibrium of active and passive forces was applied, which significantly simplifies the way of load balance. It is more favorable to treat occlusal forces, which in reality are reactions caused by the work of mandibular muscles on the surface of teeth, as active forces which directly strain the dentures. The realization of actual force balance, without the change of active and passive forces, would imply some impediments, resulting from the necessity to identify unknown muscle forces which cause a given occlusal reaction [23]. The stochastic course of occlusal loadings was replaced with deterministic model. Special attention was paid to the reflecting realistic mastication loading conditions of the denture during destabilization on the foundation.

In case of mastication, the denture is not only vertically pressed to the foundation, but also settled by oblique forces. The resulting mastication force depends not only on the surface shapes of masticatory teeth, but also on the shape and texture of food, as well as momentary spatial relation to the opposite tooth surface. Food mastication takes place through crushing on a relatively short distance, which does not exceeds 2-3 mm; however it always takes place in lateral masticatory movements of mandible, and never in anterior-posterior movements [24]. An occlusal force in the premolar zone oriented buccally under the angle of 45 degree was assumed (B100N). The force was applied in a few steps (Fig. 4): in the first step, a vertical force of 100 N (V100N); then, in the second step, a laterally oriented horizontal force of 30 (B30N) and in the third step, a 100 N horizontal force (B100N), that gives oblique mastication force of 141 N at an angle of 45 degrees.

The possibility of contact with the opposite upper denture was assumed at the non-working (balancing) side (Fig. 4). Different balancing contact conditions were simulated. An instantaneous contact was modeled with a small distance of 0,1 mm to the upper denture surface. A "delayed" contact was modeled with a displacement the distance to 2 mm. Two variants of the distance between dentures were assumed - occlusal surface of upper denture is 0,1 mm or 1,0 mm away. Interaction of balancing contacts with opposite denture was simulated with an assumption of a slide, for example after a bite in the conditions of lubrication with saliva. In the second variant blocking of the slide, which can take place on harder pieces of food or directly between teeth, was modeled.

Table 1 includes the selection of operational loading conditions considered in simulation studies of dentures, as well as physical values adopted as assessment criteria for mastication efficiency.

2.3. Verification of modelling rules

In this study we adopted a way of testing reliability of the results of calculations which constituted the verification using analytical solution for Hertz's contact of two deformable cylinders and with data provided in literature of the calculation of denture displacements and pressures beneath denture under stable loads.

Verification 1: The first verification included a comparison of the values of contact pressures calculated by MES with the values calculated analytically. Contact stresses were calculated analytically according to a formula for the contact of two cylinders [25,26]:

$$\sigma_N = \sqrt{\frac{2F}{b\frac{1}{2}(\frac{1}{E_1}+\frac{1}{E_2})}\cdot\frac{1}{2}(\frac{1}{r_1}\pm\frac{1}{r_2})\cdot\frac{1}{2\pi(1-\nu^2)}} \quad (1)$$

where F - compressive force; E_1, E_2 - elasticity modules of longitudinal cylinders; ν - Poisson`s ratio; b -length of contact of cylinders along the axis; r_1 and r_2 - cylinder radius.

Identical cylinder radius were adopted - 10 mm, and the length of contact - 10 mm, $\nu = 0{,}3$. Two variant of force loadings were adopted: F = 10 N and F = 100 N. The influence of cylinder elasticity modules were studied, with the calculations for E_1/E_2: 2000/5 (denture/ "hard" mucous membrane); 2000/1 (denture/ "soft" mucous membrane). Calculations for "soft" mucous membrane were performed exclusively for testing purposes, as the simulation studies of mastication efficiency were performed for the case of "hard" mucous membrane. The effect of increasing mesh density on contact surface from 3 mm through 1 mm to 0.5 mm (designations of "M3", "M1" and "M0.5" were adopted respectively) on the results of calculations was tested.

In Fig. 5 contact stresses between cylinders were presented (E_1/E_2 =2000/5) for the loading of 10 N and 100 N, as well as for the equivalent Huber-Mises (H-M) stress distribution. The occurrence of the largest stress in Bielajev points is visible. The comparison of contact pressures calculated by FEM with analytical solutions was presented in Fig. 6 for the analyzed changeable values of longitudinal elasticity modules of cylinders and dimensions of finite elements. In case of the ratio of the size of the element to the radius of the cylinder M0.5/r10 in the areas of the largest convexity during the application of force of 100 N overestimation of MES stress values by 8,7% occurred, while it was 4,9% during the application of force of 10 N. In case of a larger ratio M3/r10 (thinner mesh), an underestimation of -7,2% occurred for larger force, while for smaller force the biggest difference occurred in the relation to the analytical solution, as the pressure was underestimated by -34,1%. The choice of conditions for simulation studies, for which underestimation does not play any role, was discussed in the verification section.

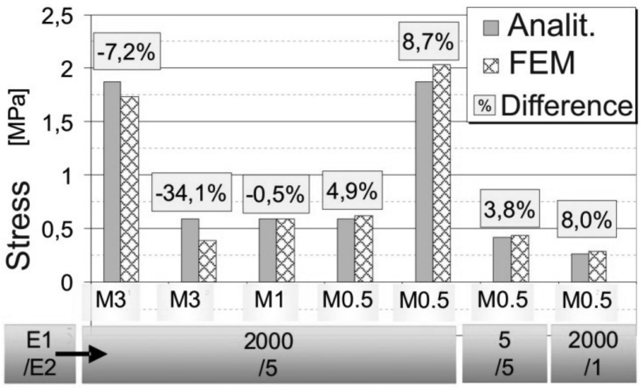

Fig. 6. The influence of mesh density on the differences in contact stress values between two cylinders calculated numerically by FEM and analytically for the values of force of 10 N and 100 N, as well as for the ratio of cylinder elasticity module of 2000/5 or 2000/1

Verification 2: The second verification was performed for the displacements of dentures on the foundation in the conditions of stable loading with a vertical force of 100 N. Vertical displacements caused by the application of a vertical force of 100 N (V100N) were -0,009 mm in the area of the posterior denture edge on the loaded side (Fig. 7a). The denture laid firmly on the foundation and it did not rise on the balancing side. In the contact area this was not observed (Fig. 7b), however small areas of microslides were noticed (approximately 0,02 mm), especially in the anterior segment. The growth of vertical occlusal force to 200 N did not cause destabilization of the denture, however the values of contact stresses increased proportionally to the loading force.

Verification 3: the third verification of the model included a comparison of pressure beneath dentures with available measurement data for stable pressure to the foundation. Calculated values of maximum pressure beneath dentures loaded with a vertical force of 100 N reached the value of 252 kPa (Fig. 7c).

2.4. The results of FEM analysis for simulation of bearing oblique mastication load

The influence of the increase of horizontal value of constituent occlusal force on the contact conditions on the surface of the mucous membrane beneath dentures and the values of contact stresses were presented in Fig. 8.

Denture displacement values in control points were shown in Fig. 9. Oblique force led to significant displacements. On the balancing side a detachment from the foundation occurred, because as a result of destabilization the flange of the denture rose. The lean of the denture was accompanied by significant slide on the foundation on the working side. Denture dropping from the foundation was prevented by the balancing contact with the opposite denture. The influence of balancing contact conditions on the loads of mucous membrane beneath dentures was presented in Fig. 10. Balancing contact conditions significantly influenced pressure values beneath denture, as well as the reaction force values on balancing contact provided in Fig. 11. Pressure and slide values beneath dentures increased together with the increase of the distance to balancing contact. Between the state of “immediate” contact and "delayed" contact an increase of pressures to 3 MPa occured and the sliding distance rose to nearly 1 mm.

3. Description of achieved results

3.1. Verification of the modeling rules

Displacement values experimentally measured within oral cavity in the conditions of controlled pressure of dentures to the foundation, are estimated to be 0,1-0,3 mm [27-30]. Experimental data concerns an average thickness of the mucous membrane 1,0-1,5 mm, which is significantly larger in comparison to an extremely thin mucous membrane selected in simulation studies. Moreover, in real systems some “clearance” is present, which is “eliminated” by pressure, but it is measured as displacements, therefore in real conditions ideal tailoring of contacting surfaces is lacking. There is also a layer of saliva, the thickness of which can exceed 100 μm [31]. Dentures included in simulation studies undergo smaller deformations due to their massive shape. Considering the factor mentioned above, displacement values were stated as correctly calculated.

In the case of oblique mastication forces transmission, which are important from the point of view of the simulation of real operation conditions, oblique subsidence of dentures occurs, which causes the largest pressure on alveolar slopes, but not on their vertices. The influence of the element in relation to the curvature of contacting surfaces was insignificant, as it was shown in the first verification. Considering the results of the first and the second verification, as well as the quality of calculations, which is important from the point of view of the purpose of this study, in the situation of bearing the oblique mastication forces, it was considered justified to resign from the condensation of the mesh surrounding the vertices, which allowed to significantly reduce the computational effort.

Denture solutions, which promote even load distribution on the foundation of soft tissue meet with more acceptance [32,33], even in case of the lack of significant differences in mastication efficiency. This fact leads us to an important conclusion. The assessment criteria of mastication efficiency is not only the ability to masticate food, which is measured objectively, for example in mesh tests. The main criteria is discomfort caused by pain, about which overloads beneath dentures decide. Therefore, a lot of work is committed to this key subject - mucous membrane overloads. Experimental data regarding maximum pressure beneath dentures are in the range of 200-350 kPa [34-41]. On the laboratory position in conducted studies [41] the application of force of 1000 N leads to the pressure of 250 kPa on the alveolar slopes on the cheek side and 80 kPa on the tongue side. In the papers [34-39] pressure values reach 310-350 kPa, however in [40] the application of a vertical force of 50 N causes pressure values of 21,1-214,1 kPa on alveolar slopes on the working side.

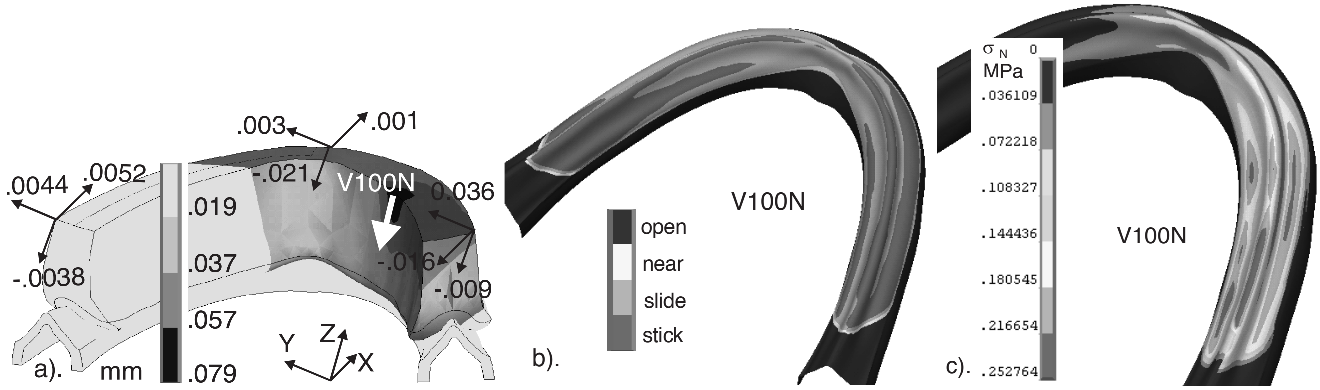

Fig. 7. The displacements of dentures caused by stable pressure applied with a vertical force of 100 N with an exact distinction of constituent displacements in three control points (a). Contact conditions (b) and the distribution of normal stresses σ_N (c) on the surface of the mucous membrane

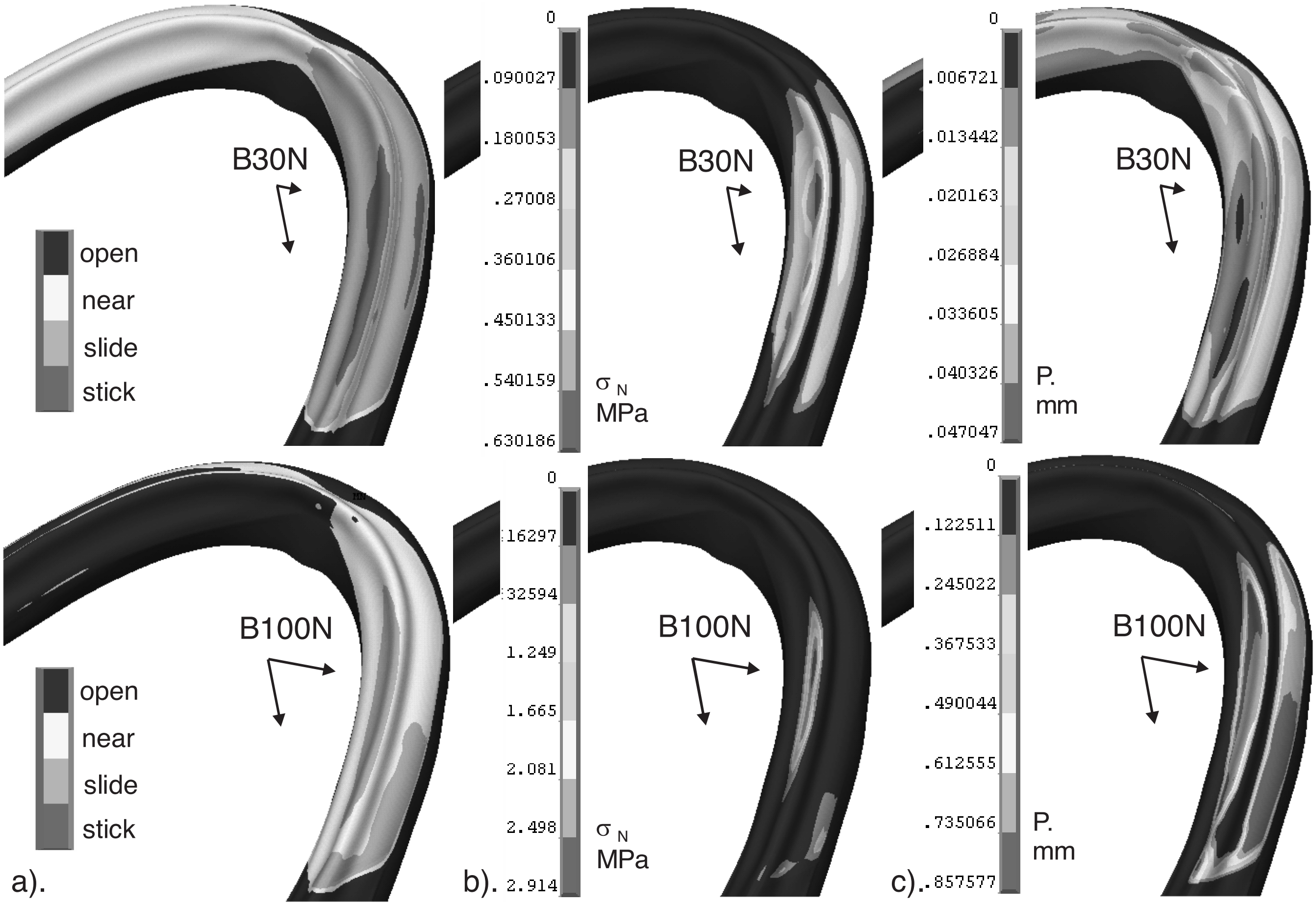

Fig. 8. Contact conditions on the surface of the mucous membrane beneath dentures (a); Distribution of normal stresses (b) and distribution of slides (c) in the phases of realization of loads of horizontal constituent mastication forces of 30 N horizontally „B30N" and 100 N horizontally „B100N"

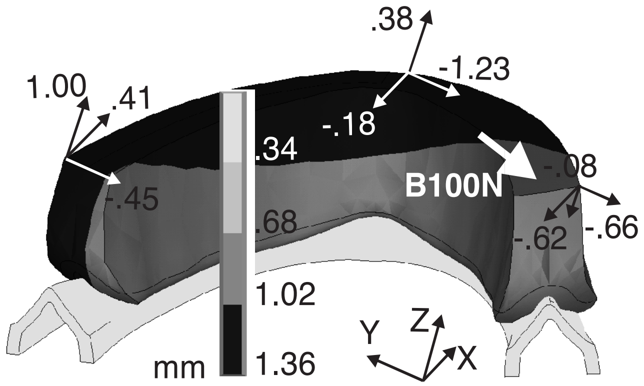

Fig. 9. Denture displacements in directions X (anterior-posterior), Y (lateral) and Z (vertical) caused by oblique mastication force „B100N"

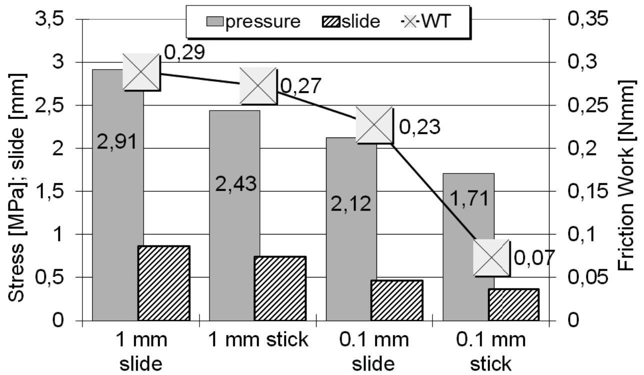

Fig. 10. The influence of balancing contact conditions on maximum pressures (MPa), slide (mm) and friction work W_T (Nmm) beneath dentures in the phase of application of oblique occlusal forces „B100N"

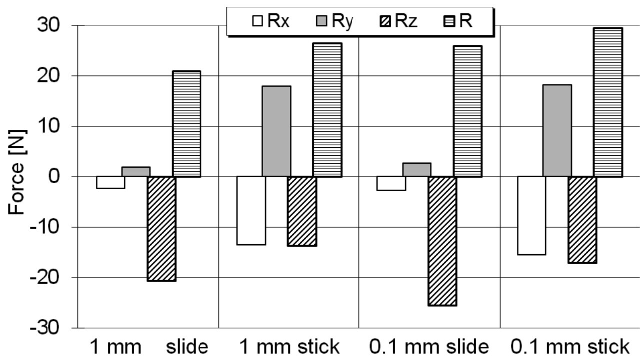

Fig. 11. The influence of balancing contact conditions on the reaction value on balancing contact (constituents and R resultant) in the phase of application of oblique occlusal forces „B100N"

Moreover, registered pressure values beneath dentures are significantly smaller than the threshold of pain sensitivity [10,11,13], which stays in clear contradiction with discomfort caused by pain experienced by the majority of denture users. Furthermore, pain sensitivity influenced by long-term use of dentures, might additionally decrease by 40% [10]. In mucous membrane tissue submitted to pressure, a decrease of the number of mechanoreceptors was observed [42]. If the factor which causes pressure is removed, it is possible to reorganize nerve endings, for example by changing a regular denture to an implant denture [43]. Pathological changes of soft tissue which occur due to mechanical injuries are commonly associated with ulcers. However, it should be highlighted that in the clinical image abrasions, and not decubitus predominate [44-47]. Skin and mucous membrane react differently to friction, even though in both cases we can observe solidifying and thickening of the epithelial layer [44]. However, in the case of skin abrasions harder tissue is formed on the surface, and under it healing processes take place [48]. Mucous membrane lacks the resistance to friction due to the deficiency of these effects.

The possibility to relate the result of previous studies conducted on dentures to real situations occurring within the oral cavity is limited to a large degree. The cause of this clear contradiction is an insufficient reflection of loading conditions. We should pay attention that in the studies conducted on physical models presented in literature [39-41] a simplified deterministic model of the dominating role of constituent vertical occlusal force is applied, which significantly differs from the actual situation, resulting from tooth shapes, mandible kinematics and functioning of balancing contacts. Measures in this study [49] performed on dentures within the oral cavity correspond to functioning conditions of dentures which are too stable and supported evenly on the foundation, which is characterized by beneficial conditions. Considering this, it is difficult to cause typical flange lift of dentures on the balancing side. On the contrary, instead of the lack of pressure larger pressure values are registered under the balancing flange than on the functioning flange [49]. Typical loads which accompany destabilization in the process of mastication, when dentures tilt and the support area decreases, [16], remain unknown. Although denture mobility on the foundation is considered to be the reason for discomfort caused by pain and development of friction injuries, previous engineer analysis has not provided the assessment of friction effects.

If friction injuries are considered the main undesirable interactions of settling dentures, the objectification of discomfort caused by pain creates the necessity to assess not only the pressure values beneath dentures, but also contact force values and slide values, especially in the conditions of significant displacements of dentures in relation to the foundation in the process of destabilization caused by mastication forces. Whereas, the significance of contact stresses on the surface of the mucous membrane as a traumatic criteria of denture interaction is shown only in literature [50,51]. However contact stress values on the surface of the mucous membrane are calculated in the paper [50] with the simplification of denture contact conditions with the foundation to the conditions of perfect adhesion. Therefore, it is difficult to relate the results to actual situations of denture destabilization. In the paper [51], in which an effort was made to numerically simulate denture slide on mucosal surface, it was stated that the risk of friction injuries increases in case of typical atrophy of toothless alveolars in the anterior segment of mandible, which causes sliding of dentures on the inclined foundation towards the front. However, common problems with frictions beneath dentures prove that friction injuries do not have to be associated with the typical inclined shape of the foundation.

In practical FEM analysis of mechanical issues of contact, it is necessary to simplify the characteristics of resistance movement on the salivary layer. Literature presents varied values of friction ratio for saliva. Saliva friction ratio on the surface of the mucous membrane decreases with the increase of movement speed. In the work [52] depending on loads and speed a friction ratio of 0,1-0,35 is given. In the work [53] significantly larger values - by 0,45 - were provided. It should be mentioned that stimulated saliva, which is secreted while mastication, has worse lubricant properties [52], which justifies lower viscosity (thinning) in comparison to non-stimulated saliva. Decrease of friction value with the increase of normal force in the range of 0,34-2,20 N is justified by the possibility of surface deformation of tissue microasperities. Important observations are included in the work [54], where the deciding influence of saliva hydration (or desiccation) on the friction ratio is proven. In case of fresh hydrated saliva the friction ratio for two people tested is between 0,02-0,06. In case of desiccation the values get higher up to 2,8-3,0, which corresponds to strong adhesion [54]. In the studies of friction of pig tongues covered with human saliva, a dynamic friction ratio of 0,16 (±0,03) was shown, while for pig tongues which were not covered with human saliva it was 0,25 (±0,03), with the displacement speed of 0,5 mm/s and normal force of 0,1 N [55]. Given the wide variety of measurement data regarding mobility resistance in numerical studies we adopted an average value of friction ratio of 0,16 [56], which can be additionally justified by the fact that the studies do not concern saliva itself, but the specific frictional pair of an acrylic denture and mucous membrane with salivary lubrication.

Currently we are lacking experimental method, which gives opportunity to differentiate the displacements for those which are caused by deformation of soft foundation and those which are caused by detachment and slide on the foundation. Experimental technique of mucous membrane load assessment beneath dentures is based on pressure measurement using differently constructed sensors [57-59]. The sensors allow a local measurement only, by averaging the pressure distribution under the sensor, depending on its size. Usually the construction of sensors allows to perform measurements only on alveolar slopes, and not on the peaks. Load assessments on the basis of pressure distribution on the whole slope surface are recently performed using special sensors (mats) laminated in foil [60]. The measurement technique has been applied for many years in the assessment of contact conditions, but is has many faults [61]. One of them is the influence of stiffness of the laminated sensor on measurement artifacts, in the form of falsified localizations of premature occlusal contacts. Our experience allows to state that also in sensors dedicated for pressure measurements on soft tissue, the foil is too stiff to perform correct measurements of pressure on the surface of the mucous membrane beneath dentures. Previously presented [60] results concern the measurements performed beneath a partial denture saddle supported on evenly shaped and convex mandibular alveolars. In case of unfavorable foundation conditions, atrophied and irregular shapes of alveolars make it impossible to adequately tailor the stiff foil to the foundation. It should be also taken into consideration that the presence of foil on the boarder of contact disturbs the state of load of soft tissue, especially the course of slide. Experimental techniques lack the possibility to assess the state of load inside the tissue.

Incorrect approach to denture mobility as the only result of the deformation of mucous membrane foundation draws attention [62]. The mucous membrane pressured with denture saddles cannot undergo deformation the size of which reaches its thickness. The range of deformation of the mucous membrane corresponding to saddle pressures is included in the range of 0,1-0,3 mm [27,29,30], which corresponds to 5-20% of deformation. Significant deformations might occur with the load of a small area, when a significant freedom of amorphous deformations is allowed, for example in a compression test of resilience using a penetrator. It could be suspected that the authors of the work [62] motivated by a significant range of deformation, which occur during indented measurements, interpret denture displacements measured during mastication as tissue deformations. It should be underlined that the methods of kinesiographic measurements of denture displacements on the foundation are not suitable for the assessment of mucous membrane deformation. Displacement values of 0,1-0,3 mm, which correspond to the studied deformations, remain in the range of an error of the measurement method.

The majority of previous efforts for numerical modeling of load bearing beneath dentures show a clear lack of knowledge in accepting correct assessment criteria for the state of load. In numerical studies we do not usually consider pressures beneath dentures [63-65]. Only in the works [4,50] we refer to the area of anti-decubitus techniques, documenting the occurrence of areas of higher pressure and clotting in the mucous membrane, remotely located from each other, while simultaneously responsible for decubitus development [66-67].

3.2. An estimation of denture mastication efficiency

In clinical practice mastication efficiency shows downward tendencies together with the degree of reduction of toothless alveolars of bone foundation [68]. Occlusal force values decrease on average from 150 N to 60 N [68], respectively for atrophy degrees of 3 and 4, as well as 5 and 6 (according to Atwood). In case of unfavorable foundation conditions, which were analyzed in this paper, traumatic interaction of dentures and mastication inefficiency are typical. Calculated values of pressure on the foundation are compliant with the above mentioned fact. The level of pain sensitivity of the mucous membrane during denture destabilization has been exceeded almost five times. It could be estimated that the elimination of pain requires the reduction of occlusal load to approximately 30 N. These values are too small to masticate larger foods.

Denture mobility on the foundation is also considered as a determinant of mastication efficiency [69]. Displacement values calculated as model calculations are compliant with the results of measurements within the oral cavity [13], in which the displacements reach 1,1 mm during the load of the first molar. It should be mentioned that displacement values measured during their use [13] correspond strictly to the phase of mastication of food, which corresponds to accepted model conditions. Measurements within the oral cavity also show that correct balancing contacts are ahead of occlusal pressures on the functioning side [15]. Firstly, contact in the area of the second molars occurs; after 32-48 miliseconds in the area of the first molars, and after further 2-48 ms in the area of premolars [15]. The deficiency of denture balance causes mastication inefficiency in practice. The results of simulation remain in perfect convergence with the mentioned fact. Should the distance to opposite denture in the model be increased, which corresponds to the situation of „delayed" balancing contacts, significantly worse functioning conditions were observed. Values of pressure beneath dentures responsible for pain increased significantly. Pressures were bearing in the conditions of significant slide due to which the largest values of friction, which determine the risk of developing friction injuries, occurred in the areas of slopes on the side of the tongue. Therefore the results of the stimulation are compliant with the fact that the intensification of traumatic interaction is related with the lack of adequate balancing contacts and balance of lower dentures. The lack of ability of a patient to look for balancing contact and bilateral distribution of food mass make it impossible to achieve stabilization. Gaining such abilities requires sufficient psychomotor performance in the situation of varied operation of occlusal forces. Whereas, rehabilitation of activities which are not based on repetition, is difficult, especially that it does not go hand in hand with the age of toothless people. Additionally, mastication efficiency might be worsened by the lack of ability to use the tongue to prevent the lower denture, adhering to the upper denture by food, from rising [19]. The results of the studies also confirm that in case of unfavorable conditions of the foundation to gain stabilization it is necessary to use implants [19,70].

4. Conclusions

Significant progress has been achieved in the studies on functioning conditions of mucous-borne dentures through FEM destabilization simulation under oblique mastication loads. Actual functioning conditions of dentures were imitated thanks to the introduction of possibility models of denture detachment from the foundation of the mucous membrane and slide in the conditions of salivary lubrication. The presented methodology of the studies gives opportunities for individual numerical verification of mastication efficiency of planned denture depending on various features of dentures, such as their shape, positioning of the teeth in the arch and material properties of dentures.

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