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Denture foundation tissues loading criteria in evaluation of dentures wearing characteristics

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Analysis and modelling

ABSTRACT

Purpose: Rationalization of rules determining shape of dentures functional characteristics requires knowledge of loading state of tissue denture foundation.
Design/methodology/approach: During FEM numerical modeling there was made evaluation of loading state of denture foundation tissues pressed by a hard denture and relined by a silicone layer.
Findings: Maximum shear is observed under mucous surface at bone on the side of process prominence. Soft tissues injuries and pain discomfort might result from exceeding both tolerances of pressure and shear, which maximum values are located in the opposite areas. Maximum pressure values are present in central areas at tips of edentulous ridges. The layers of relining material results in a decrease and balancing of maximum pressure values. It decreases tendencies of slip and frictional injuries occurrence by means of reducing tangential stresses on the mucous interface. Nevertheless, the transfer of part of loadings on ridges slopes results in increased shear inside of the tissue at the side of the convexity. In bone tissue at the tips of edentulous ridges there is observed decrease of principal stresses and the lack of significant changes of equivalent von Mises stresses.
Research limitations/implications: One of the model simplifying assumptions was the assumption of isotropic linear elasticity of materials mechanical characteristics and denture adherence to its foundation.
Practical implications: Recommended to relining are injuries occurring in the central area of bone convexities. If, in spite of a proper denture fit, there is still a typical ulceration at the side of the ridges convexity, use of relining increases shear of those area of the tissue, conducing development of a typical deep ulcer located usually from the bone towards the surface of soft tissues.
Originality/value: Tangential stresses and loads on mucous surface are not the only one criterion of evaluation and diagnosis of mucous membrane loading state.
Keywords: Biomaterials; Mechanical properties; Denture relining; Tissue

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1. Introduction

Determining conditions of mechanical loading in tissue surrounding implants or prosthesis functioning in organisms belongs to one of the basic tasks of engineering of biomaterials [1-5]. A typical example of that is an evaluation of mechanical interactions on dental prosthetic solution [6-10]. For many years now, there can be observed a focus of dental engineering on expensive dentition reconstruction methods that use implants and aesthetic materials. Understandable is here the significant financial support of surveys focused on directions yielding incomparably higher profits than conventional dentures, unit price of which, along with labor of a dental technician reaches app. the equivalent of 100 Euro. In expensive methods of implant treatment, a comparable cost is achieved already by temporary dentures, which are added to total treatment cost in an insignificant position. Moreover, expensive dentition reconstruction methods become a field for spectacular engineering successes. The most crucial data that is necessary to design wear properties, which are the real loading forces and not less important support conditions. In case of fixed dentures there can be described a significantly lower range of variation. Due to that fact prediction of durability can be much more precise in case of those solutions, as well as the most crucial, as far as treatment successfulness is concerned – creation of properties in a manner that ensures physiologically tolerated loadings level on surrounding tissues. Numerous difficulties of engineering analyses in case of dentures working on mucous membrane, the fact that the awaited success would be less spectacular and lower financial benefits most probably constitute the reason of created remarkable disproportion between the number of studies on traditional dentures and those more expensive. Engineering engagement in development of expensive methods of edentulouism treatment is not reflected in the improved life quality of less wealthy people. Most of the patients affected by edentulouism have to adopt themselves to the cheapest traditional, so called mucous borne dentures working on the basis of natural denture foundation bearing capacity – soft tissues of mucous membrane.

It should be mentioned here that more than the half of mucous borne dentures wearers signal discomfort resulting from painful sensations, as well as frequent mucous membrane injuries, reaching even 20 % of all cases [11,12]. Interesting is also here the fact that the hard to be cured mucous membrane prosthetic stomatopathy is perceived as further effect of mechanical overloads.

Due to the sense of discomfort, part of the patients resign from wearing dentures at all, especially the lower one, acceptance of which is incomparably more difficult than the upper due to anatomical conditions related to remarkably smaller mandibular denture foundation area. Wearing difficulties triggered by the painful sensation very often create serious constraints in patients professional and personal life, which connected with the still lowered age of people affected by edentulouism, confirms the social weight of the problem. Worth mentioning is the fact that the further effect of the lack of dentures acceptance are irreversible changes of the face articular and osseous system.

A method that decreases the discomfort and mucous membrane injuries is relining of the hard dentures saddles, usually made of silicones or plasticized polymethacrylates. Due to the loss of plasticizers in oral cavity environment polymethacrylate, relatively quickly lose their capacity of load relieving in surrounding tissues. Hence, silicones are usually used for long-term relining.

Due to the effects of mucous membrane loading, determining required material characteristics of those layers constitutes the crucial issue. In many cases, even long experience and intuitive biomechanical feeling of the doctor are insufficient to achieve positive results of the treatment. In such situations, priceless is the possibility to juxtapose clinical effects with their quantitative evaluation based on objective principles of mechanics.

It has been defined that relining material should be characterized by its ability to dissipate energy during cyclical mastication load rather than the creep [13]. Although, a direct transfer of laboratorial tests carried out on samples onto a real system does not meet the requirements of basic principles related to selection of material and constructional characteristics based on a complete knowledge of loads distributed in the analyzed system. In experiments on physical models there is achieved information on distribution of load, which is assumed to be the sole criterion for evaluation of denture impact on foundation tissue [14]. Yet, the loading of tissue under the surface of mucous membrane, determining of which in a living organism is impossible, belongs to the unknown. The appropriate analysis method in this case is a model analysis, e.g. FEM numerical analysis. Nevertheless, all attempts of numerical modeling of mucous membrane loading are characterized by the lack of recognition during assumption of proper mechanical criteria [15,16]. In FEM analyses evaluation of mucous membrane loading is realized according to Huber-Mises criterion, commonly used in engineering. Still, in the field of techniques counteracting bedsore, during numerical analyses and „in vivo" experiments documented was [17-19] occurrence of increased pressure and shear located in various areas – equally responsible for creation of the bedsore [20,21].

The aim of the presented work was identification of values of particular stress state components in mucous membrane occurring during transfer of occlusal forces. Afterwards, determining in which way modification of dentures saddles resilience, based on introduction of a 2 mm thick layer made of relining material, influences redistribution of loads impacting occurrence of injuries and painful sensations.

2. Methodology

Evaluation of loading of soft tissue beneath denture, to which applied were occlusal forces was carried out on the basis of MES (Algor software). According to the rules of MES analyses there were made some simplifying assumptions, which are aimed at reduction of numerical analysis computational costs to the level adapted to available computational techniques, maintaining reflection of system characteristics in the range that ensures determining of searched values.

Prepared spatial model of a denture resting on a mandible foundation is presented in Fig. 1. Isolated were only tissues constituting denture supporting zone. There was assumed a constant shape and system of tissues along mandible. For the purposes of the analysis assumed was foundation shape that is characteristic for difficult prosthetic conditions, i.e. with a strong atrophy of mandible ridges, where small convexity and inclination of slopes results in a decrease of tissue capable of transferring mastication forces. There was assumed an ideal shape of ridges. It was done for the purposes of eliminating the phenomenon of overlapping of stress concentration effects in one area, which would result from local unevenness. In the model of the denture there was simplified the shape of the teeth, omitting irregularities of occlusal surfaces unnecessarily increasing number of finite elements laying beyond the area of interest.

In the first of the prepared models hard denture saddles directly adhered to mucous membrane foundation. The second of the numerical models was prepared in order to examine the influence of silicone relining on redistribution of loads on mucous membrane. On the interface between denture and mucous foundation, there was introduced an even 2 mm thick layer, executed in a manner that is typical for long-term relining, i.e. at the „cost" of denture saddles (Fig. 1).

There were analyzed stresses and strains of mucous membrane and bone tissue of the prosthetic foundation caused by denture displacements under applied vertical load of 100 N. Further boundary conditions created constrains bearing degrees of freedom at bottom surface of mandibular bone. Model fixing method is justified by insignificant influence of mandible deformations on mucous membrane loadings, which mainly result from dentures movements. There was assumed an ideal stick condition on the interface denture / foundation. This reflects situation, in which there are no local slips, or denture detaching off the foundation. This assumption to a large degree corresponds with a situation of a stable transfer of mastication loads. In geometrically complex models and strongly diversified elasticity of contacting bodies, when there are problems with achievement of reliable results and convergence after there are introduced contact phenomena [16], it is recommended [22] to carry out output analyses in a linear range. One of the further assumptions remarkably simplifying calculation procedures was assuming linear-elastic isotropic material mechanical characteristics. Mucous membrane, apart from the initial chewing phase [23], functions within the range of instantaneous strains. Examining state of loadings that accompany mastication, mucous membrane mechanical characteristic can be successfully determined by a linear relationship. Foundation tissues injuries most frequently occur in case of a poor resiliency of mucous membrane foundation. Hence, there was assumed modulus of elasticity value located in the higher range: E = 5 MPa [24]; little tissue compressibility has been reflected to some extent by high value of Poisson` coefficient $\nu = 0.49$. Silicone relining materials are characterized by insignificant rheological effects [25]. On the other hand, non-linear deviations of silicones mechanical characteristics for the purposes of numerical modeling are successfully approximated by the elasticity modulus [26], value of which for silicones available on the market is between 1 and 20 MPa. In calculations there was assumed a value reflecting mucous membrane elasticity – 5 MPa. Young modulus for cortical bone was assumed at the level of E = 17 GPa; for spongy bone E = 600 MPa; at Poisson`s coefficients in both cases $\nu = 0.3$. For polymethacrylate of denture saddles and false teeth there was assumed E = 2000 MPa and $\nu = 0.3$.

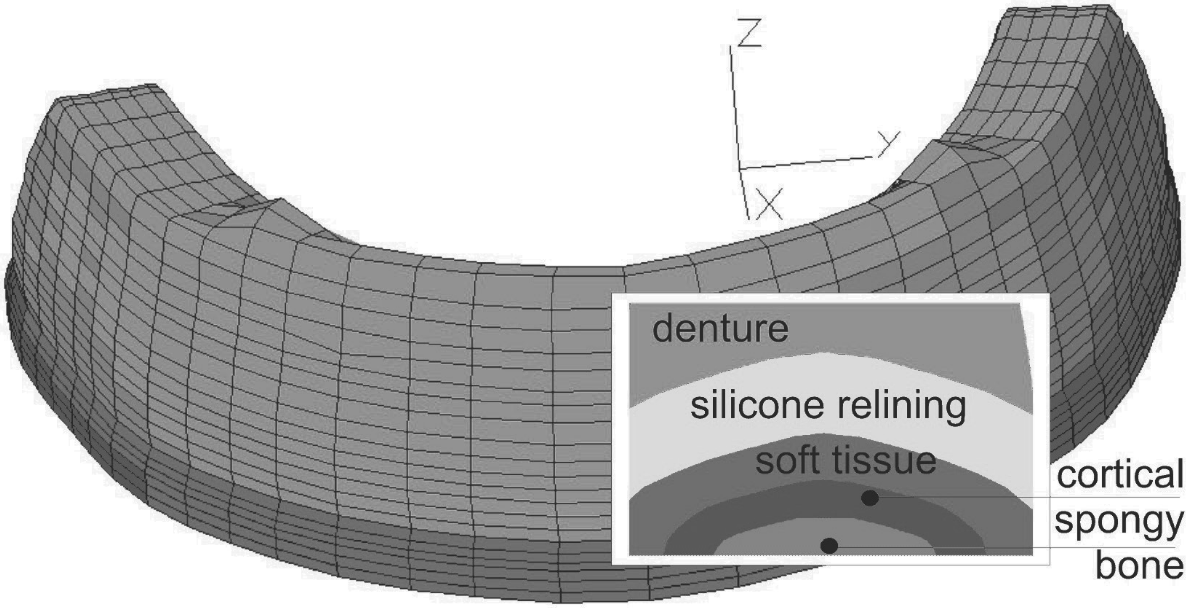

Fig. 1. Spatial denture model with a cross section showing thickness of the assumed layers and shape of the atrophied alveolar ridges

3. Results

3.1. Criteria determining loading of prosthetic foundation soft tissue

Defined model assumptions related to simplifying of rheological phenomena in soft tissues reduce the possibility of a direct reference to the real system. Although, achieved results regarding tissues reaction to mechanical loading correlate to stresses evoked by immediate elastic deformation, which subsequently point out trends of changes that take place in tissues under the influence of various loading conditions. Reaction, even to the long-lasting tissue loading, visco-elastic materials and anisotropic characteristic is possible for the purposes of forecasting, on the basis of tendencies of mechanical values in linear-elastic static models.

MES analyses of stress conditions that accompany wear loadings made it possible to isolate crucial areas that are dangerous due to the level of particular stresses components. There was examined not only the state of loading on the mucous membrane surface, which in the already presented studies was treated as the sole criterion for evaluation of dentures solutions wearing characteristics, but also the attention was paid to the distribution of loads beneath the interface.

In Fig. 2 (a), there is shown a cross-section perpendicular to the dental arc in the area where the loading force was applied. Represented are also the distribution double maximal shear stresses (directly show the biggest difference between values of principal stresses), whereas in Fig. 2 (b) minimum stresses (compression) in mucous membrane. In Fig. 2 (c) and (d) there was presented the distribution of principal maximal and minimal strains.

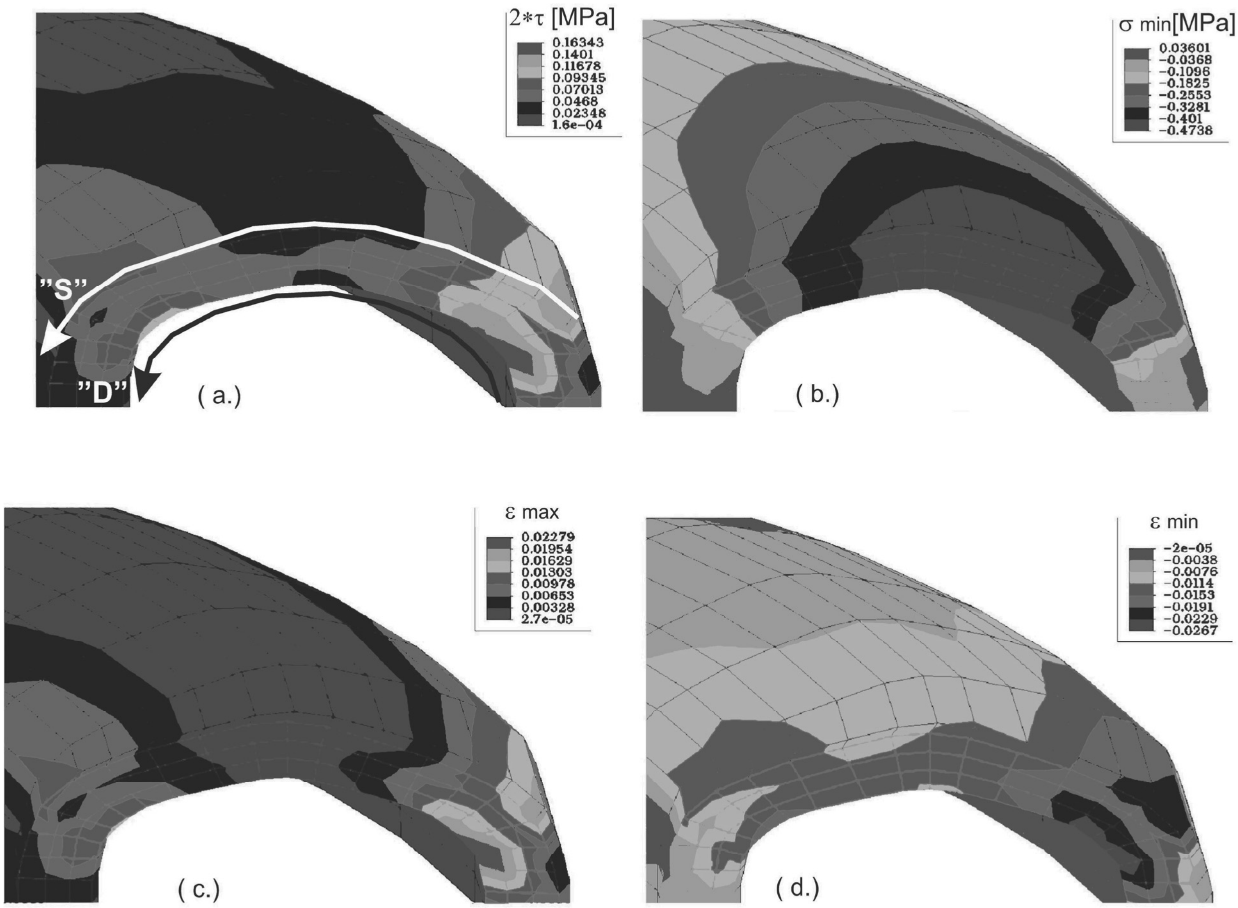

Fig. 2. Mucous membrane loading in a cross section perpendicular to dental arc in the point, where loading force was applied: (a) distribution of doubled maximum shear stresses ($2^* \tau_{max}$); (b) distribution of minimum stresses (compression); (c) distribution of maximum principal deformations; (d) distribution of minimum principal deformations

For shear, which is as much responsible for ulcer as compression [20,21], there are assumed much higher values beneath mucous membrane. Shear stresses concentrate at the sides of edentulous bones of the ridges. Asymmetry, based on reduced shear from the lingual side, is created by system geometry: dental arc. In real conditions, load distribution on sides of the ridges depends directly from additional horizontal component of the mastication force directed outwards or inwards of the dental arc depending on food location on the occlusal tooth surface.

On the surface of the mucous membrane close to denture margin there is also a visible local increase of shear. The reason for that are local deformations created by denture edges pressed into the tissue. Nevertheless, shear deeper inside of the tissue has nothing in common with this phenomenon. Shear concentration at the bone results from highest differences between tension and compression created by deformations of the tissue compressed and pushed out by the whole surface of the denture. These differences are visible on the presented distribution of principal deformations. In the central area of the ridge the minimum deformations do not reach the highest values. Hence, minimum principal stresses, which occur in this area of the tissues are not connected to the minimum deformation value. These are pushing denture saddles that limit the freedom of movements of the quasi-incompressible tissue and lead to pressure increase. In none of the analyses of mucous membrane loading attention has been paid to tangential on the mucous surface. In parallel attention is drawn by the fact that most of the mucous membrane injuries are those related to frictional soreness [27,28]. On the other hand, friction together with a simultaneous shear created by distortional deformation significantly reduces allowable pressure [27,29]. Frictional injuries result from denture slip on the mucous membrane. In case if there is present a lubrication salivary layer, overcoming frictional resistance is determined by friction coefficient from the range of 0.1-0.7 [28,30]. Although, a denture slipping on the saliva layer isolating it from the tissue cannot create attritions. Hence, there have to occur local phenomena of direct contact of rubbing surfaces. During biomechanical evaluation of denture solutions there should be determined tendencies of changes of tangential tresses on the surface related to occurrence of frictional phenomena.

Anticipation of clinical effects requires knowledge not only of surface pressure, but also location of shear areas under tissue surface. Discomfort and injuries resulting from frictional effects should be perceived as resulting from tangential stresses on the surface.

3.2. Influence of silicone relining layers on loading of prosthetic foundation soft tissue

Fig. 3 presents loading state redistribution in soft tissues created by the used relining material. Due to the transparency of the picture, presented was distribution of pressure and shear, omitting the earlier described deformations phenomena.

Profiles in Fig. 3 show comparison of shear and compression (here absolute values) along "S" and "D" paths for hard and relined dentures. Paths went from the lingual side outwards, as shown in Fig. 2: path "S"- close to the mucous membrane surface; whereas path "D" – deeper inside close to the bone surface. Diagrams show that relining results in balancing of surface pressure and their decrease in the central area above bone convexity.

In spite of assumed simplified conditions of denture adherence to its foundation, the trend of changes of tangential stresses relation to those normal shows information on influence of the relining on frictional effects. In Fig. 3 (c) there is presented a tendency to slip occurrence. Relining not only reduces the highest pressure by means of their balancing, but also decreases the possibility of slip, which is of the fundamental importance for protection against attrition. It has been discovered that that relining results in a significant increase of shear, both at the bone and on the surface. This increase results from increased distortional deformation of tissues as a consequence of balancing pressure, i.e. transfer of its part from the central area onto the slopes. Although, relining also makes surface shear stresses peaks blur and moves them if they are located close to saddles edges in case of a hard denture. This creates a justification of the above mentioned statement, which was related to lack of any dependence between the local stresses concentration at the edge of the denture and a concentration deeper in the tissue close to the bone.

It is therefore stated that analyses carried out on the basis of single pressure criterion or shear criterion lead to a single-sided incomplete interpretation of the phenomena [19,20]. Values of maximum surface pressure are determinant of the compression in central area only and do not tell anything about the level of shear stresses inside of the tissues.

Relining material layer influences the system in two ways. By means of balancing pressure on the surface it leads to reduction of painful sensations and reduces the risk of injuries on the bone convexity. On the other hand, by eliminating disadvantageous loading effects in the central area, there can be developed other equally dangerous typical deep ulcer going from the bone towards the surface of soft tissues.

In the light of the presented results it appears that it is absolutely necessary, to determine on the first place the type of injury or location of painful sensation. Not before then it would be possible to connect it with indicators of the loading state: shear, pressure or tangential forces at the surface, which point out the tendencies related to occurrence of frictional injuries. Finally, knowledge of those relations would make it possible to replace intuitive and accidental decisions by a rational determining of wearing characteristics. Results of the presented studies confirm the necessity of a better identification of loads distribution on the mucous surface and in particular taking into account the possibility of denture detaching and slipping. Hence, during further studies there should be connected together all clinical facts. First, the influence of silicones on frictional phenomena on the surface of mucous membrane, injuries of which are in most cases classified as frictional [27,28]. The second, basis of dentures biomechanics: stabilizing on the so-called balancing contacts, i.e. counteracting destabilizing influence of occlusal loads at the working side by means of occlusal contacts on the opposite wings at the balancing side.

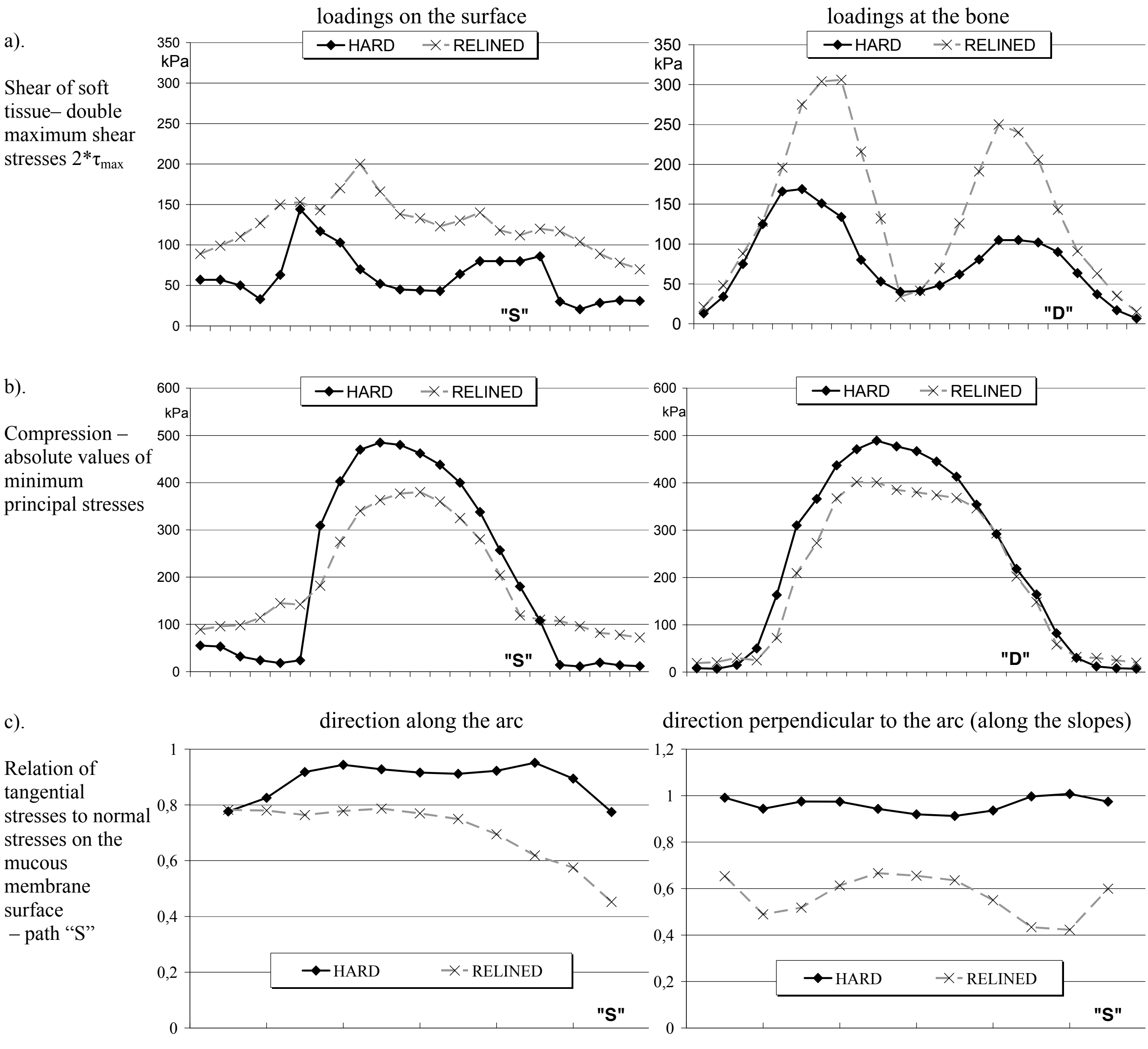

Fig. 3. Comparison of stresses on mucous membrane surface along "S" path deep in the soft tissue at the bone along the "D" path for hard and relined denture: (a) distribution of stresses 2*τmax, (b) distribution of stresses, c) tendencies of movements

3.3. Influence of silicone relining layers on redistribution of loadings in bone tissue of edentulous ridges of prosthetic foundation

Prosthetic treatment is aimed at restraining atrophy processes of edentulous ridges continuously progressing in the period of edentulouism. Mechanisms of ridges atrophy processes have not been completely examined yet. Loading state change of the bone tissue of alveolar ridges after loss of teeth is assumed to be the factor intensifying atrophic processes. On one hand denture restores mastication function and activates mechanical stimulants responsible for maintenance of the bone level state, and on the other hand, mechanical overloads of ridges peaks caused by non-physiological pressure of denture saddles is assumed as the factor that might accelerate the process of atrophy.

Dentures relining has a remarkable influence on the bone tissue loading state created by the denture saddles pressure. In Fig. 4 there is presented the distribution of circumferential and longitudinal stresses in cortical bone wall, at the peak of ridges beneath the area where the occlusal force of 100 N caused by a hard denture is applied. Presented stress components showed highest variety in the function of relining thickness. In Fig. 5 there are presented changes of circumferential and longitudinal stresses in lower and upper areas of cortical bone wall in function of relining thickness.

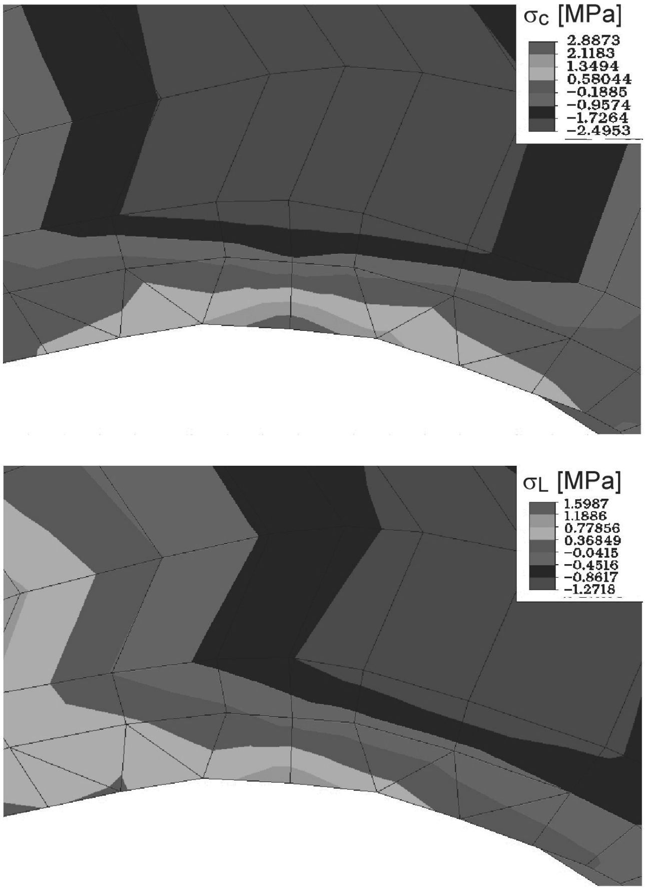

Fig. 4. Circumferential and longitudinal stresses at cortical wall of edentulous processes beneath hard denture

On the diagram there is shown a remarkable effect of loading relieving upper areas of ridge wall (σCT-Circumferential at Top of the wall, σLT-Longitudinal at Top of the wall). It should be stressed that the values of equivalent von Mises stresses, which are not shown on the diagram have not significantly changed as far as the function of relining thickness is concerned. This result shows that, similarly to the case of the soft tissue, the analysis of loading state in the criterion of reduced stresses according to the hypothesis of distortional strain energy might lead to an incorrect evaluation of the influence of denture relining on the state of bone tissue of the prosthetic foundation.

The effects of the reliving found out in model conditions cannot however be directly transferred onto the real system. In model conditions comparison of the system before and after relining was carried out with assuming of identical conditions of denture loadings by occlusal forces. Yet, in real conditions of oral cavity after relining, there might occur an increase of occlusal forces that level the relieving effects of the relining, due to the decreased soft tissue painful sensations, as well as increased denture stability. On the other hand, after relining, there is observed an increase of chewing efficiency to higher extent than the increase of maximum occlusal forces. A direct non-physiological overloading is commonly treated as disadvantageous for the state of bone tissue. Hence, a loading scenario based on the increased frequency, might even function favorably. Hence, generally, it should be assumed that denture relining causes advantageous effects for bone tissue of edentulous ridges.

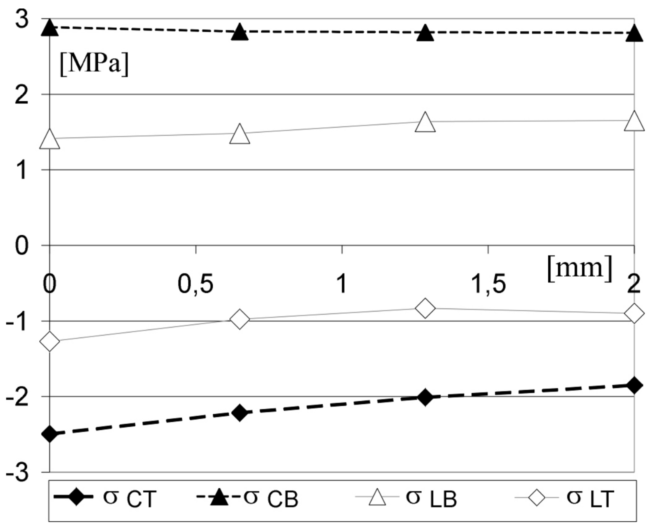

Fig. 5. Influence of silicone relining thickness on stress state components in cortical bone wall of edentulous processes σCT-Circumferential at Top of wall; σCB-Circumferential at Bottom of wall; σLB-Longitudinal at Bottom of wall; σLT-Longitudinal at Top of wall

4. Conclusions

Numerical evaluation of phenomena related to transfer of loading by prosthetic foundation tissue of the mandible remarkably supplemented previous incomplete knowledge regarding occurrence of tissue injuries and painful sensations. It has been defined that the basis of the correctly conducted studies creates the assumption of equal criteria: maximum values of normal stresses located at the surface of the mucous membrane, in central area of peaks of the edentulous ridges, as well as maximum values of shear stresses, located beneath mucous membrane surface at the bone on the sides of the ridges. Using the described methodology, there was determined the influence of used soft layers made of materials relining hard denture saddles on redistribution of loads in soft tissue. Relining material results in decreased stresses in central area, although at the same time significantly increasing shear at the sides of bone convexities of edentulous ridges. Assumption of maximum normal stresses values (pressure) on the surface, achieved, for instance directly on the basis of measurements, as the sole evaluation criterion of dentures wearing characteristics leads to negligence of very important information related to the danger of development of typical deep ulcer at the sides of bone convexities. Areas of increased shear defined in the described studies point out at the necessity of verification of the commonly approved principles related to creation of denture wearing characteristics and diagnosis of tissues loading. It has been stated that the 2 mm thick relining layers, which are commonly evaluated as the most effective, in case of occurrence of typical ulcer injuries at the slopes of the ridges cannot be used. Similarly, while eliminating injuries in the central area, it is necessary to examine painful sensations in the mentioned particular areas in order to prevent the occurrence of ulcer.

Denture relining influences loading of bone tissue in the area of the peaks of edentulous ridges, which, to some extent eliminates the effects of overloading that result from non-physiological pressure caused by dentures saddles.

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