Modelling of the tooth contact through one-layered mouthguard

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Abstract. The work deals with the modelling of the contact of the teeth with and without taking into account a single-layer mouthguard made of ethylene vinyl acetate (EVA). The problem is considered in an axisymmetric formulation with the contact interaction including a friction along the conjugate surfaces. An optimal finite element mesh with a gradient dense element distribution near to the contact areas was used. A series of numerical experiments for various values of indentation force (ranging from 50 to 500 N) was carried out, a significant drop in the intensity of stress in hard tissues of the teeth was established by more than 60% when using a mouthguard. In this case, the zone of maximum stress concentration is not of a local nature, as in contact without taking into account the mouthguard. The dependences of the maximum level of stress intensity for two variants of design schemes and the intensity of plastic deformations on the strength of indentation are obtained. The distributions of contact pressure and tangential stress are obtained, it is found that the maximum contact pressure for the model taking into account the mouthguard is 3 times less than in the model without taking into account the prototype structure.

1. Introduction

Methods of mathematical modeling for problems of complex spatial configuration are widely used in many fields of research: aircraft engineering [1], construction [2], medicine [3], metallurgy [4], biomechanics, etc. Often, such structures operate under difficult conditions of deformation, including within the framework of the mechanics of contact interaction, and possess a large number of contact surfaces. Now, the biomechanical behavior of systems has been becoming actual: contact interaction of bone and articular cartilage [5], deformation of the hip endoprostheses with antifriction layer [6], peristaltic flow of lithogenic bile through the stenosed biliary duct [7], deformation analysis of hard tissues teeth at their contact interaction with the mouthguard [8], etc. During the last decades, it is possible to note the special interest of domestic and foreign scientists in biomechanical modelling of dentistry tasks: numerical analysis of the effect of inhomogeneity of dental tissues on the center of rotation [9], modelling of initial movements of the elements of the dentoalveolar system under the influence of orthodontic loads [10], experimental and numerical study behavior of materials of a mouthguard [11], numerical modelling of the occlusion [12], analysis of the contact interaction of the two teeth with mouthguard [13], and others.
At the same time, the urgency of the problem of preventing the injuries of the dentoalveolar system with the use of individual protective equipment in the form of prosthetic structures, which is highlighted in [14-16], forms a new class of biomechanical problems in the dentoalveolar system. A large number of studies in this field are devoted to the analysis of the effect of prosthetic structures on the dentoalveolar system of man and the reduction of the load on the dentition when doing sports and heavy physical labor [8, 11, 14]. Another relevant area of the research is the analysis of the properties of sports dental mouthguard materials [11, 15, 17-19]. For example, in [15] a great deal of attention has been paid to the analysis of various options for personal protective equipment in the form of dental mouthguard made of ethylene vinyl acetate. The team of authors [11] carried out a series of full-scale experiments to analyze the properties of the materials of the three-layer mouthguard: EVA and A-silicone.

In connection with the urgency of using protective structures in the form of dental mouthguards to prevent injury to the dentoalveolar system, there was a need for computer modeling of biomechanical behavior, both the structures themselves and the materials from which they were made. The current research tasks are: biomechanical analysis of the influence of the properties of the mouthguard material on the deformation behavior of hard tooth tissues; mathematical modeling of the contact interaction between teeth of different geometric configurations for a wide range of physiological loads; complex interdisciplinary study of the changes in the stress-strain state of the dentofacial system when using mouthguards (contact pressure, contact tangential stress, intensity of stress in hard tissues of the teeth, etc.).

The purpose of the work is the numerical FEA of the stress-strain state during the contact between teeth taking into account / without taking into account of the mouthguard. Moreover, the influence of the mouthguard properties influence was analyzed.

2. Problem statement
The problem of numerical modeling of the contact interaction for two computational schemes is considered in the paper (figure 1): the first is the contact of the teeth of the upper (1) and lower (2) dentition without regard for the mouthguard, the second is the contact of the tooth pair through the prosthetic construct (3). The physical and mechanical properties of EVA, the material from which the dental mouthguard was made, were obtained from the results of a series of experiments [11]. Young's modulus for the elastic region was 17.1 ± 1.58 MPa, Poisson's ratio $\nu = 0.46$. Elastoplastic mechanical behavior of EVA was revealed by tension tests [20].

![Figure 1. Computational schemes of the teeth: a) with mouthguard contact and b) without mouthguard contact.](image-url)
The mathematical problem statement of the contact problem includes
- equilibrium equation
\[ \text{div} \hat{\sigma} = 0, \quad \bar{x} \in V \]  \hspace{1cm} (1)
- geometrical relation
\[ \hat{\varepsilon} = \frac{1}{2} \left( \nabla \hat{u} + (\nabla \hat{u})^T \right), \quad \bar{x} \in V \] \hspace{1cm} (2)
- Hooke’s law
\[ \sigma = \lambda I_1(\hat{\varepsilon}) \hat{I} + 2\mu \hat{\varepsilon}, \quad \bar{x} \in V_1 \cup V_2 \] \hspace{1cm} (3)
where \( \lambda \) and \( \mu \) are Lamé parameters; \( \hat{\sigma} \) is the stress tensor, \( \hat{\varepsilon} \) is the strain tensor, \( \hat{u} \) is the displacement vector, \( \bar{x} \) is the radius-vector of arbitrary point position, \( I_1(\hat{\varepsilon}) \) is the first invariant of the strain tensor, \( \hat{I} \) is the identity tensor; \( V \) is the considered domain \((V = V_1 \cup V_2 \text{ for the first computational model, } V = V_1 \cup V_2 \cup V_3 \text{ – for the second computational model}), V_1 \) and \( V_2 \) are the domains occupied by the teeth of upper and lower rows, respectively, \( V_3 \) is the volume occupied by the mouthguard.

To describe the mouthguard behavior the deformation theory of elastoplasticity has been chosen, the physical relationships of which have the form:
\[ \hat{\sigma} = \frac{2\sigma_u}{3\epsilon_u} \left( \hat{\varepsilon} - I_1(\hat{\varepsilon}) \hat{I} \right) + 3KI_1(\hat{\varepsilon}) \hat{I}, \quad \bar{x} \in V_3 \] \hspace{1cm} (4)
where \( \sigma_u = \sqrt{3I_2(\hat{\sigma})} \) and \( \epsilon_u = \frac{2}{\sqrt{3}} \sqrt{I_2(\hat{\varepsilon})} \) are the second invariants of stress tensor deviator \( \hat{\sigma} \) and strain tensor deviator \( \hat{\varepsilon} \), \( K \) is the bulk modulus; \( \sigma_u = \Phi(\epsilon_u) \) is the functional relation depending on the mechanical uni-axial EVA behavior.

The mathematical statement (1)-(4) is supplemented by boundary and contact conditions \( S_\sigma \): a constant functional load is applied at the boundary, which varies from 50 to 500 N (indentation force) and bending is forbidden; on the boundary \( S_y \), displacements along the \( y \) coordinate are forbidden; on the contact boundaries \( S_{\text{cont}} \), contact interaction is considered with allowance for friction along the conjugate surfaces and all types of contact state (adhesion, slippage, detachment) with a constant coefficient of friction 0.3 [21].

Of greatest interest are the nature of the contact \( S_K \) in the contact zones for the first design scheme and \( S_{K_1}, S_{K_2} \) for the second calculation scheme.

3. Results
To analyze the numerical solution convergence of the contact problem, a series of numerical computations was performed [22]. The contact problem assumes an interaction between two teeth through single-layered mouthguard. The problem is solved by FEM. ANSYS software was adopted to solve the problem. Axisymmetric finite elements with Lagrangian approximation were used. According to the convergence analysis, it was revealed that the finite element mesh with 26 000 nodes and gradient thickening element to the contact zones provides an optimally accurate and time consuming solution. The maximum element size is 2.50E-04 m, the minimum size is 6.25E-05 m.

The stress-strain state comparison analysis between contact of teeth with/without mouthguard was performed. As a result, the stress intensity distribution was obtained (figure 2). The maximum stress intensity versus teeth compression load is shown in figure 3.
When a pair of teeth contacts the elastoplastic single-layered mouthguard, a significant drop in the maximum level of stress intensity is observed: for the tooth from the upper dentition more than 60%, for the tooth from the lower dentition more than 74%. In this case, the zone of maximum stress intensity is not localized, as in contact without taking the mouthguard into account.

For the scheme taking into account the mouthguard made from EVA, the maximum stress intensity is lower than without taking into account the mouthguard: for the tooth from the upper dentition, on average, 2-2.5 times less; for the tooth from the lower dentition 2-3.5 times less. The stress intensity of the mouthguard is minimal, which is related to the physical and mechanical properties of the material and an appearance of elastoplastic deformation. Figure 4 shows a qualitative picture of the distribution of the intensity of plastic deformation in the mouthguard, depending on the level of the functional load.

Figure 4 reflects the nature of the change in the intensity of plastic deformations with increasing indentation strength. Plastic deformations occur at a load of 100 N, near the area of the contact with the tooth from the lower dentition. As the load increases, the area of the plastic deformations increases and, under a load of 300 N, is observed near the contact area with the tooth from the upper dentition. The maximum intensity of plastic deformations in the mouthguard is observed in zones of contact interaction. Figure 5 shows the maximum intensity of plastic deformations as a function of the indentation intensity.

As one would expect with an increase of the indentation force, the maximum level of plastic deformation increases by a nonlinear law and at a maximum load it is 28%.
Figure 4. Distribution of the plastic deformations in the mouthguard at various loads.

Figure 5. Maximal intensity of plastic deformations vs load.

4. Conclusion
In this study, a numerical model of the contact interaction of two teeth of the upper and lower dentition is constructed with and without taking into account the EVA single-layer mouthguard, and the deformation of the biomechanical contact node is analyzed within the framework of the deformation elastoplasticity theory for a wide range of functional loads (50-500 N). A convergence analysis of the numerical solution is conducted with a change in the degree of discretization of the system with the choice of the optimal finite-element model of the decomposition of the construction with a gradient decrease in the size of the element to the contact region. The distribution of stresses and deformations in a pair of teeth is obtained at contact interaction at a different level of physiological load.

When analyzing the results of a series of numerical experiments, the following was obtained:
- When a pair of teeth contact through a prosthetic structure, the maximum contact pressure level is, on average, 3 times lower than when contacting the elements of the maxillofacial system of a person without taking into account the mouthguard. The contact tangential stress is 3-4 times less than the contact pressure. The effect of elastoplastic deformation of the mouthguard on the distribution of contact pressure and contact tangential stress is established.
- With the contact interaction of a pair of teeth through a prosthetic construction, a drop in the maximum intensity of stress in the solid tissues of the teeth is observed. On average, the maximum
intensity of the tooth tension from the lower dentition is 3.5 times less when contacting the mouthguard than on contact without a mouthguard, and a 2.5 times increase in the tooth from the upper dentition.

- With increasing load, the area of the plastic deformations in the mouthguard increases, while at a load of 500 N the maximum level of plastic deformation intensity does not exceed 30%. The effect of plastic deformation at the contact zone is seen in the distribution of the contact pressure and the contact tangential stress.

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