The Influence of the Three-Layer Mouthguard on the Stress-Strain State of a Pair of Opposing Teeth

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Abstract. The aim of the study was to consider the contact interaction of a pair of opposing teeth with and without taking into account the three-layer mouthguard. The strain-stress analysis of the biomechanical model was undertaken within the framework of the elastoplastic stress-strain theory. 7 geometric configurations of the mouthguard were considered within a wide range of functional loads which were varied from 50 to 500 N. We obtained the distribution of the stress and strain intensities in a pair of opposing teeth during contact interaction at a different level of physiological load. The dependences of the maximum level of stress intensity and the intensity of plastic deformations in the biomechanical model were established. Contact parameters were considered near the zone of dental occlusion.

1. Introduction
A biosocial cycle of the human body depends on such vital physiological processes as respiration and digestion, which are greatly influenced by the state of dentofacial system. In addition, teeth perform an aesthetic function, serve to process food mechanically and articulate speech [1, 2]. However, these functions may be impaired due to dental injuries that often occur in sport activities. For instance, in team kinds of sport, serious tooth injuries are the result of simultaneous impacts: falls, blows to the jaw, direct contact with a sports equipment. In power sports, thinning of enamel and tooth decay are caused by longstanding mechanical impact [2-4].

At the moment, the issues of biomechanical modeling aimed at preventing dental traumas in sports are of particular interest to scientists. Currently, one of the most effective ways to reduce the chance of injury or concussion of the brain, both during training and during competitions, is the usage of mouthguard or gumshield as a personal protective equipment [1, 4-7]. Due to the relevance of the usage of sports mouthguards, numerical modeling is required to describe the biomechanical behaviour of the protective devices and the materials, they are made of [8-9].

The aims of this paper are: a biomechanical analysis of the influence of the mouthguard material properties on the deformation behaviour of dental hard tissues; numerical modeling of contact interaction of a pair of opposing teeth taking into account protective devices of different geometric configurations within a wide range of physiological loads; a comprehensive interdisciplinary study of the stress-strain state (contact pressure) of a person’s dentofacial system when using mouthguards.

2. Problem statement
The frictional contact interaction of a pair of opposing teeth was modelled with and without taking into account the three-layer mouthguard (figure 1).
Figure 1. Computational schemes of contact interaction between a pair of teeth: a) without mouthguard; b) through three-layer mouthguard; 1 is maxillary tooth; 2 is mandibular tooth; 3-4 are three-layer mouthguard; 4 is a layer of A-silicone.

The influence of the geometrical configuration of the mouthguard on the stress-strain state of the biomechanical model is considered in this paper. Two types of the total mouthguard thickness are considered near the zone of dental occlusion $h_m = 6 \pm 7\ mm$ and three types of the maximum interlayer thickness $h_p = 2 \pm 4\ mm$. The following types of geometrical configurations were regarded: 1 is $h_m = 6\ mm$, $h_p = 2\ mm$; 2 is $h_m = 6\ mm$, $h_p = 3\ mm$; 3 is $h_m = 6\ mm$, $h_p = 4\ mm$; 4 is $h_m = 7\ mm$, $h_p = 2\ mm$; 5 is $h_m = 7\ mm$, $h_p = 3\ mm$; 6 is $h_m = 7\ mm$, $h_p = 4\ mm$.

Mouthguard is a three-layer protective device: the main material is Eva (ethylene vinyl acetate); the interlayer is A-silicone. The material properties were obtained within a framework of an interdisciplinary study by the research team of PNIPU, PSMU and PSNIU [10]. Mechanical properties of materials are shown in a table 1.

| Material Name              | Young’s modulus $E$ (MPa) | Poisson’s ratio $\nu$ |
|----------------------------|--------------------------|-----------------------|
| Tooth material (tooth enamel) | $80.4 \cdot 10^3$       | 0.3                   |
| EVA                       | 17.3                     | 0.46                  |
| A-silicone                | 0.3                      | 0.49                  |

It was shown in the series of experiments that the Eva material exhibits elastoplastic properties, thus the dependence $\sigma - \varepsilon$ was plotted in [11]. To describe the behavior of the Eva material, the elastoplastic stress-strain theory is chosen. The mathematical statement is described in [11] and includes: equilibrium equations, physical and geometric relations, contact boundary conditions. The solution was realized in a plane statement with a constant thickness of the biomechanical model of 8 mm.

The mathematical problem statement (1)-(4) is supplemented by boundary conditions and symmetry conditions: a constant load is applied at the boundary $S_a$ and varies from 50 to 500 N.
(indentation force); bending is prohibited; vertical displacements are prohibited at the boundary \( S_{\text{b}} \); symmetry conditions are applied at the boundary \( S_1 \).

3. Results
The solution of the problem of the contact interaction of a pair of teeth through a three-layer mouthguard was implemented in the ANSYS Mechanical. An analysis of the convergence of the results of the numerical solution of the problem from the degree of discretization of the system was implemented earlier in [12]. It was established that a finite element mesh with a gradient with increased density of elements to contact zones gives an optimal solution to the problem in terms of accuracy and counting time. The maximum element size is 2.50E-04 m, the minimum is 6.25E-05 m. The finite element decomposition of biomechanical nodes, considered in this paper, was performed similarly to the previously selected grid.

The analysis of the influence of the thickness of the mouthguard and the interlayer of A-silicone on the stress-strain state of the node as a whole and the contact zone in particular was implemented. As a result, there were obtained: the fields of the distribution of stress intensity in biomechanical nodes and the intensity of total and plastic deformations in the mouthguard; the maximum intensity-stresses plots for the hard tissues of teeth and the intensity of plastic deformations-indentation force plots for the mouthguard. The parameters of contact interaction near the zone of dental occlusion were analyzed.

The field of stress intensity distribution for \( F = 300 \) N is presented in figure 2 taking into account the 6th variant of the protective dental device with \( h_m = 7 \) mm, \( h_p = 4 \) mm.

![Figure 2](image)

**Figure 2.** Stress intensity distribution in the teeth and mouthguard at indentation force 300 N: 1, 2 are computational scheme 1, 2 respectively; a is the maxillary tooth; b is the mandibular tooth.

In comparison with the computational scheme without mouthguard, the maximum stress intensity decreased by approximately 15 and 17 times for the maxillary and mandibular teeth, respectively, in the computational scheme with mouthguard. In addition, stress intensity fields were redistributed while considering contact interaction through the mouthguard. There were no local zones of maximum stresses near the zone of dental occlusion, the distribution of the stress intensity level became more uniform. The stress intensity in the mouthguard was minimal, which may be due to the physico-mechanical properties of the material or elastoplastic deformation of the mouthguard. The analysis of the influence of the geometric characteristics of the mouthguard on the deformation behaviour of the teeth was of a particular interest.

The dependence of the maximum level of stress intensity in hard tissues of teeth on the indentation force is shown in figure 3.
Figure 3. Maximum stress intensity-force plots for teeth contacting through the mouthguard: 1-6 are geometrical configurations of the mouthguard; a is the maxillary tooth; b is the mandibular tooth.

The total thickness of the mouthguard and the thickness of the interlayer have a significant impact on the deformation behaviour of the teeth. For a maximum indentation force of 500 N, the minimum values of the maximum stress intensity are 31.2 and 28.4 MPa with a mouthguard thickness of 6 and 7 mm, respectively. These values are observed for mouthguards with an interlayer thickness of 2 mm. Moreover, the volume of the Eva material in the zone of dental occlusion is maximum, due to the elastoplastic properties, the material is better adapted to the geometry of the opposing teeth and thus affects the stress reduction in the hard tissues of the teeth. In the maxillary tooth, the use of a 7 mm thick mouthguard reduces stress intensity by more than 15.75 times, a 6 mm mouthguard shows a less significant indicator of a decrease in stress intensity level (approximately 14 times on average). The decrease in the maximum level of stress intensity in the mandibular tooth is more significant and averages approximately 18.25 and 19 times for mouthguards with 6 and 7 mm thickness, respectively.

The value of plastic deformation in the main material of the mouthguard is of the particular interest. Figure 4 shows the dependence of the maximum level of plastic deformation in the mouthguard on the indentation force.

Figure 4. Maximum plastic strain intensity-force plots for the mouthguard: 1-6 are geometrical configurations of the mouthguard.

It can be noted that with an increase in the indentation force, the maximum level of plastic deformations increases according to a nonlinear law. Its maximum value is 26.3% with a maximum indentation force of 500 N. The maximum value of plastic deformations is observed in the model taking into account the 4 variants of the prosthetic design with $h_m = 7$ mm, $h_p = 2$ mm, which has the maximum decrease in the level of stress intensity in hard tissues of teeth.

Consider the contact parameters in the zone of dental occlusion during frictional contact interaction of opposing teeth through the three-layer mouthguard. Figure 5 shows histograms of the dependence
of the maximum level of contact pressure and contact tangential stress on the indentation force. The distribution of contact parameters is shown for the biomechanical model for the 6th variant of the protective device.

![Figure 5. Dependence of the maximum level of contact pressure (a) and contact tangential stress (b) on the indentation force in the zone of dental occlusion during frictional contact interaction of opposing teeth through the three-layer mouthguard: light grey is maxillary tooth, dark grey is mandibular tooth.]

The maximum contact pressure is greater in the mandibular tooth, and the maximum contact shear stress is greater in the maxillary tooth (figure 5). In addition, it can be noted that the contact shear stress is 4 or more times less than the level of contact pressure and is more susceptible to the geometric configuration of the mouthguard. With an increase in the indentation force, the value of the maximum contact pressure practically does not change; the maximum tangential stress is more sensitive to the load level.

4. Conclusion
As part of the study, a numerical model of the problem of contact interaction of a pair of opposing teeth was constructed with and without taking into account the three-layer protective dental device made of ethylene vinyl acetate and A-silicone. The analysis of the deformation behaviour of the biomechanical contact node within a wide range of functional loads of 50-500 N is performed. The influence of the thickness of the mouthguard and the layer on the stress-strain state of the biomechanical node as a whole is studied. The distribution of stresses and deformations in a pair of teeth during contact interaction at different levels of physiological load is obtained. When analyzing the results of a series of numerical experiments, it was established:

- When a pair of teeth comes into contact through a prosthetic structure, the maximum level of contact pressure is on average 10 times lower than when a person’s teeth and jaw are in contact without taking into account the prosthetic structure. Contact shear stress is 4 times less than contact pressure. The effect of elastoplastic deformation of the mouthguard on the nature of the distribution of contact pressure and contact shear stress is established.

- With the contact interaction of a pair of teeth through a prosthetic design, a drop in the maximum intensity of stresses in the hard tissues of the teeth is observed. On average, the maximum intensity of tension in a tooth from the upper dentition during contact through the mouth guard is 11-15 times less; for a tooth from the lower dentition is 11-19 times less.

- Influence of the thickness of the layer of individually adapted mouthguards on the deformation behaviour of hard tooth tissues: the greatest decrease in the level of stress intensity is observed when the thickness of the mouthguard is not 2 mm, since during contact deformation the volume of the main mouthguard material in the tooth closure zone is maximal and adjusts to the geometry of the tooth pair during plastic material flow; with an increase in the thickness of the interlayer, the decrease in the
level of stress is less than that of a mouthguard with an interlayer of 2 mm by 3 and 10% with an interlayer thickness of 3 and 4 mm, respectively.

- The effect of the mouthguard thickness on the deformation behaviour of hard tooth tissues: a decrease in the maximum level of stress intensity in the hard tissues of mouthguards with a thickness of 7 mm is more by an average of 10 and 4% for teeth of the upper and lower dentition, respectively.

- With an increase in load, the area of plastic deformations in the mouthguard increases, while at a load of 500 N, the maximum level of intensity of plastic deformations does not exceed 20%. The effect of plastic deformation on the contact zone is manifested in the nature of the distribution of contact pressure and contact shear stress.

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