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Comparative analysis of mechanical behavior of the tooth pair contacting with different mouthguard configurations

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Abstract. Sport mouthguards are an important piece of athletic equipment. They are used to prevent sport injuries of the dentofacial system. Paper presents comparative analysis of mechanical behavior of the tooth pair contacting with the mouthguard. Four contact types are considered: contact without mouthguard, contact with single-layer mouthguard, contact with three-layer mouthguard (with A-silicone thickness of 1.5 mm), contact with three-layer mouthguard (with A-silicone thickness of 3.5 mm). The axi-symmetric contact problem is solved with taking into account of the friction and all types of contact. We revealed a number of patterns in the results of computations with varying of indentation force in the range of 50-250 N. In the case of mouthguard contact (with A-silicone thickness of 3.5 mm), we obtained the dramatic decrease of maximal stress intensity. The maximal stress intensity vs indentation force dependence is close to linear. The silicone layer has an influence on the contact parameters magnitude and distribution. Dependence between strain intensity vs indentation force is non-linear.

1. Introduction

Due to the widespread occurrence of maxillofacial sport injuries [1] or professional injuries [2], there is a demand of studies related to the dentofacial system biomechanics. Application of new kinds of patient-specific devices made of contemporary materials is aimed at improving the quality of life of patients [2-5]. There is a wide range of research topics in the dental biomechanics: the center of rotation [6], modeling of the initial tooth movement under orthodontic stress [7], using 3D scanning technologies [8], numerical modeling of bite [9], shape memory alloy clamps applications [10], etc. A large number of studies are aimed at analyzing and solving the problems related to mouthguard usage during sports [1, 11-15]. Sports mouthguards and mouth protectors are different names for the same thing: a device worn over your teeth that protects them. Mouthguards are an important piece of athletic equipment. There are two types of sport mouthguards for contact sports and non-contact sports. Here is the mouthguard for non-contact sports is analyzed.

Recently, the new concept of individualized three-layer mouthguard (made of EVA and A-silicone) for the athletes in non-contact sports was developed at Perm State Medical University (Perm, Russia) [4, 14, 11].

Paper presents comparative analysis of mechanical behavior of the tooth pair contacting with the mouthguard. Four contact types are considered: contact without mouthguard, contact with single-layer mouthguard, contact with three-layer mouthguard (with A-silicone thickness of 1.5 mm), contact with three-layer mouthguard (with A-silicone thickness of 3.5 mm).

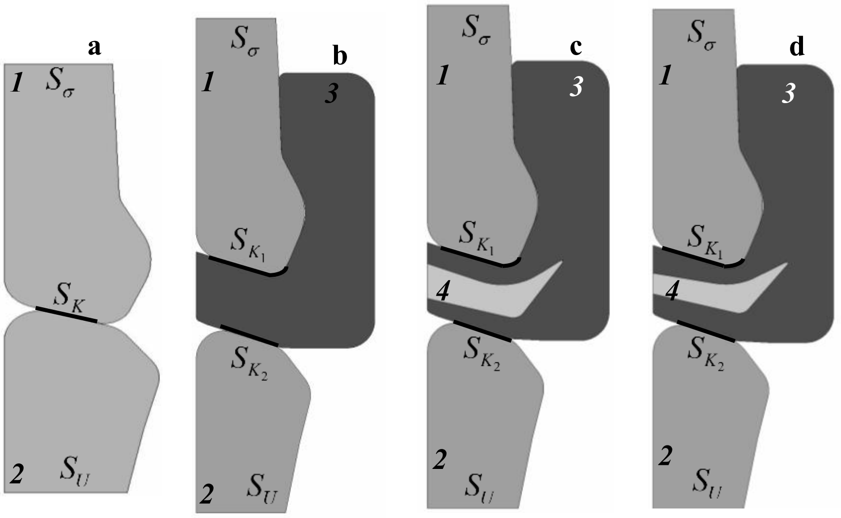

Figure 1. Computational schemes of contact interaction between a pair of teeth: a is without mouthguard; b is through single-layer mouthguard; c, d are through three-layer mouthguard (with A-silicone thickness of 1.5 and 3.5 mm, respectively).

2. Problem statement

Four cases of tooth contacting with mouthguard were considered (Figure 1): a is contact of upper tooth (1) and lower tooth (2) without mouthguard, b is contact of teeth and single-layer mouthguard (3), c and d are contact of tooth pair with three-layer mouthguard with A-silicone layer (4) with maximal thickness of 1.5 mm and 3.5 mm, respectively. Maximal dimensional parameters of upper tooth are height is 10 mm and width 6 mm, maximal dimensional parameters of lower tooth are height 8 mm and width 7 mm.

Mathematical problem statement includes equations of equilibrium, physical and geometrical relations [11]. Boundary and contact conditions are following: at the boundary S_σ, the constant functional load is applied varying from 50 to 250 N (indentation force) and bending is banned; at the boundary S_U, vertical displacements are prohibited; at the contact boundary S_{cont}, the contact interaction with friction (friction coefficient is equal to 0.3) and all types of contact (sticking, slipping, sticking-off) are considered. In computational schemes (c), (d), we did not take into account the A-silicone layer contact with other layers. Surfaces of teeth occlusion are S_K, S_{K_1}, S_{K_2}.

Mechanical properties of mouthguard materials was obtained in paper [4]. It was shown that the Young's modulus of EVA is 17.1 ± 1.58 MPa and Poisson's ratio is equal to $\nu = 0.46$; the material was exposed to demonstrate elastoplastic behavior. It was shown that EVA material exhibits elastoplastic properties, thus the dependence $\sigma - \varepsilon$ was plotted [11]. The Young's modulus of A-silicone is 0.34 ± 0.1 MPa and Poisson's ratio is equal to $\nu = 0.49$. The properties of the material of a pair of teeth are the properties of the tooth enamel. Young's modulus and Poisson's ratio were $E = 80.4 \cdot 10^3$ MPa and $\nu = 0.3$, respectively.

3. Results

In work an analysis of the convergence of the results of the numerical solution of the problem of the contact interaction of a pair of teeth was carried out, taking into account the degree of discretization of the system in the protective tire model. The influence of the geometric configuration of the protective prosthetic structure on the stress-strain state of the biomechanical assembly as a whole and the parameters of the contact zone, especially on the surface of the teeth closing, was considered. In the framework of a series of experiments, fields of stress and strain intensity distribution, regularities of change of contact parameters, as well as the dependence of maximum values of stress intensities and strains on the indentation force were obtained. For an example of the nature of the distribution of stress intensity σ_{int} fields, figure 2 shows the distribution for all considered models for the value of the indentation force 200 N.

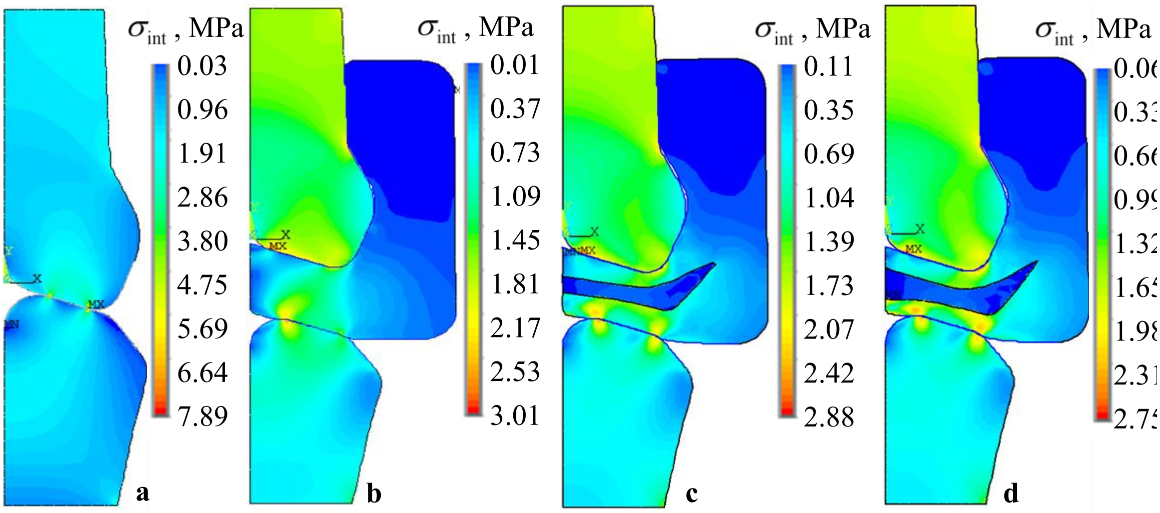

Figure 2. Stress intensity distribution in the teeth and mouthguard at indentation force 200 N: a is without mouthguard; b is through single-layer mouthguard; c, d are through three-layer mouthguard (with A-silicone thickness of 1.5 and 3.5 mm, respectively).

For cases b–d, a decrease of the maximum stress intensity is observed. The maximum stress intensity is observed on the surface of the closure of the teeth, while using the prosthetic structure, the nature of the stress intensity distribution does not contain local zones of maximum stress. Upon contact of a pair of teeth through a protective tire, a drop in the maximum level of stress intensity is observed: for a single-layer mouthguard (b), on average, by 61.85%; for three-layer mouthguards (c) and (d), on average, by 63.5% and 65.15%, respectively. It should be noted that the maximum stress intensity of the tooth in the lower dentition is approximately 5% lower than that of the tooth in the upper dentition. The dependences of the maximum stress intensity on the indentation force, which is shown using the example of the tooth of the upper dentition, are shown in figure 3.

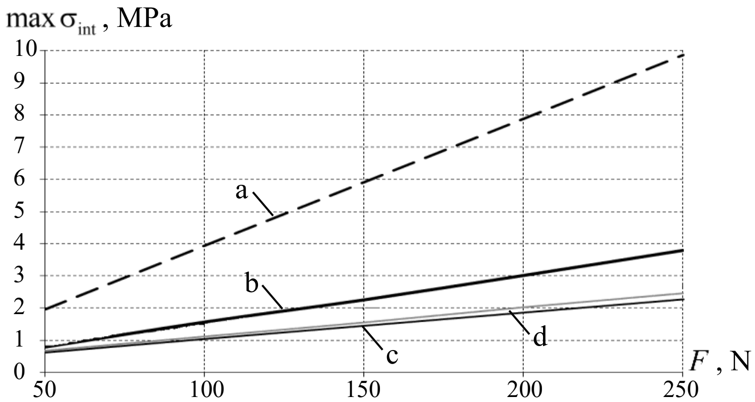

Figure 3. The $\max \sigma_{int}$ vs F in the upper tooth: lines a–d correspond to cases a–d.

The minimum stress intensity is observed when a pair of teeth contact through prosthetic structures with an A-silicone layer. As the indentation force increases, the difference between $\max\sigma_{\text{int}}$ the computational schemes, taking into account the single-layer mouthguard and three-layer protective prosthetic structures, increases, while the dependence on the indentation force is close to linear for all considered computational schemes. With an indentation force of 250 N, the maximum stress intensity in the hard tissues of the teeth decreased by more than 75% when using a three-layer prosthetic structure, and when using a single-layer mouthguard - by 60%.

Of particular interest is the nature of the distribution and the level of contact pressure on the surface of the closure of the teeth. Figures 3 and 4 show the contact pressure distribution fields for all the previously considered design schemes for an indentation force of 200 N.

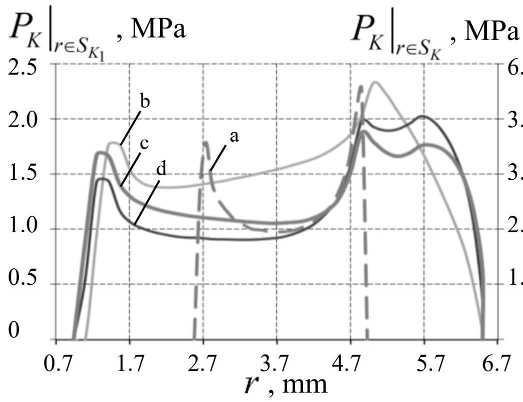

Figure 4. Contact pressure on S_{K_1} and S_K: lines a–d correspond to cases a–d.

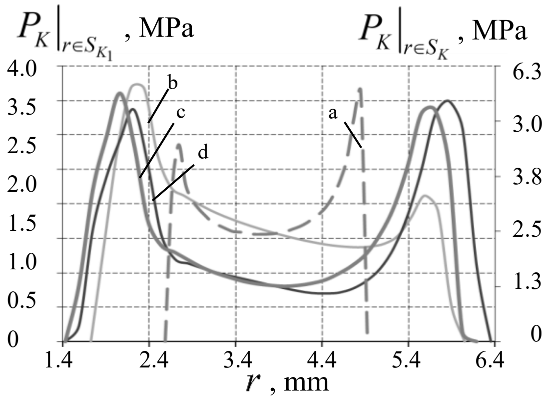

Figure 5. Contact pressure on S_{K_2} and S_K: lines a–d correspond to cases a–d.

The nature of the distribution of contact pressure is not uniform with peak levels p_K in the region of the maximum intensity of stress. The introduction of an A-silicone interlayer into the protective mouthguard had the most significant effect on the distribution of contact pressure: near the tooth closure surface S_{K_1}, the level of maximum contact pressure decreased by approximately 13% compared to the design diagram (b); on the contact surface S_{K_2} there is a more uniform distribution of contact pressure with two zones max p_K up to 3.5 MPa. For all three models of prosthetic structures, a decrease in the level of contact pressure is observed: on average S_{K_1} for a single-layer mouthguard (b) by 59.3%, for a three-layer mouthguard S_{K_2} (c) and (d), on average, by 64.56% and 66.7%, respectively; on a single-layer mouthguard (b) by an average of 35.8%, for a three-layer mouthguard (c) and (d) an average of 38.7% and 47.9%, respectively.

Since the main Eva material of the three considered variants of the geometrical configuration of prosthetic structures works within the framework of the deformation theory of small elastoplastic deformations, the nature of the distribution of plastic strain intensity in kappa is of interest. Figure 6 shows the nature of the distribution of strain intensity in the prosthetic structure at an indentation force level of 250 N

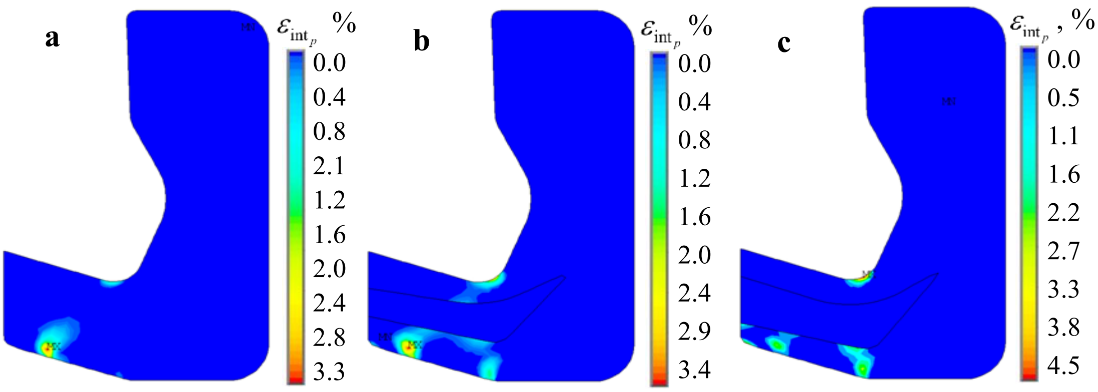

Figure 6. Plastic strain distribution in the mouthguard (case b).

It is worth noting that the maximum intensity of plastic deformations is observed near the tooth closure surface and does not exceed 5% at maximum indentation force. In the design schemes (b) and (c), the maximum $\varepsilon_{\text{int}_p}$ is close to the zone of contact with the tooth of the lower dentition; for the design scheme (c), the maximum $\varepsilon_{\text{int}_p}$ is observed near the zone of contact with the tooth of the upper dentition.

Figure 7 shows the dependence of the maximum level of plastic deformations in prosthetic structures of different geometrical configuration.

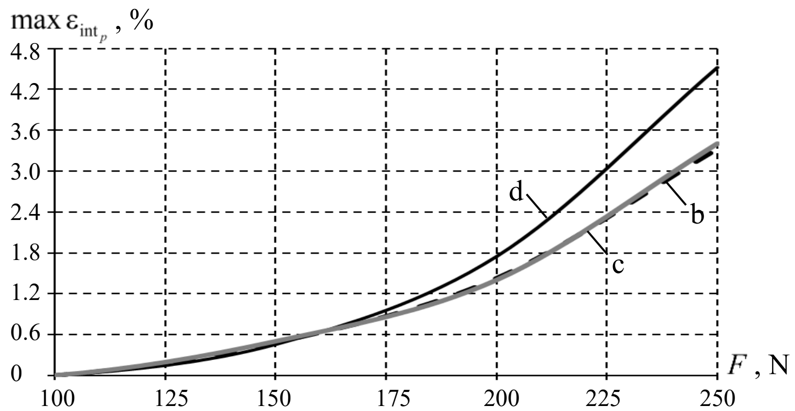

Figure 7. Dependence of $\max \varepsilon_{\text{int}_p}$ on F : lines b–d correspond to cases b–d.

The nature of the dependence $\max \varepsilon_{\text{int}_p}$ on the indentation force is not linear. For the three considered variants of the prosthetic design, the first plastic deformations appear when the indentation force is more than 100 N. For the design schemes (b) and (c), the maximum level of plastic deformations differs slightly. In the prosthetic design of the design scheme (d), the level of plastic deformations is higher than a maximum of more than 1%.

4. Conclusion

As part of the study, a numerical model of the problem of contact interaction of two teeth of the upper and lower dentition was constructed with and without consideration of the protective prosthetic structure of different geometric configuration (single-layer and three-layer). The analysis of the deformation behavior of the biomechanical contact node in the framework of the theory of deformation elastoplasticity under different functional loads is performed. The distribution of stress and strain intensities is obtained for all the models considered. When analyzing the results of a series of numerical experiments, it was established:

- Upon contact of a pair of teeth through a protective tire, a drop in the maximum level of stress intensity in the tooth of the upper dentition is observed: for a single-layer mouthguard, on average, by 61.85%; for a three-layer mouth guard with a layer of A-silicone 1.5 mm thick – by 63.5% and for a three-layer mouth guard with a layer of A-silicone 3.5 mm thick – by 65.15%. The maximum stress intensity of the tooth of the lower dentition is lower than that of the tooth of the upper dentition by approximately 5% in all variants of the design schemes.
- The maximum level of contact pressure when using a three-layer prosthetic design is reduced by approximately 13% in the zone of contact of the tooth of the upper dentition compared with the design scheme with a single-layer mouthguard. The maximum level of contact pressure in the vicinity of the tooth of the lower dentition has small differences for all variants of the dental splint.
- The maximum decrease in the level of contact pressure is observed in the construction of a three-layer mouthguard with an A-silicone interlayer with a thickness of 3.5 mm: in the zone of contact with the tooth of the upper dentition below by more than $\max P_K$ 66%; in the zone of contact with the tooth of the lower dentition - by 47%.
- The dependence of the level of intensity of plastic deformations on the indentation force is not linear, for all computational schemes it does not exceed 5%. In this case, the zone of localization of the maximum plastic deformations of a single-layer mouthguard and a three-layer mouthguard with an A-silicone interlayer with a thickness of 1.5 mm is located near the tooth of the lower dentition. In a three-layer mouthguard with a 3.5 mm A-silicone interlayer, the nature of the distribution of plastic deformation differs from the other two options considered, the zone of maximum plastic deformation is observed near the tooth of the upper dentition.

In general, prosthetic constructions with an A-silicone layer make it possible to reduce the level of stress intensity in the hard tissues of the teeth and the level of contact pressure by a larger amount than a single-layer prosthetic structure.

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