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CONTENTS

RESEARCH OF BIOMECHANICAL SYSTEM “DENTITION - SPLINT” RIGIDITY USING CAD/CAE METHOD OF MODELING

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Annotation. *The objective of the study is to determine the optimal position of the splinting construction of the maxillary dentition in children at mixed occlusion depending on the formation of the root and dual directions of functional load of the teeth. The object of the study is three-dimensional computer models of the biomechanical system (BS) of the maxilla with a splinting system for dentition fixing. To meet the targets, models of tensely-deformed state (TDS) of the maxilla BS with splinting structures of the dentition have been made using CAD / CAE methods and computed tomography (CT) data.*

Due to analysis of the results obtained, the qualitative characteristics of displacement and stress fields were established. Teeth having 70 % of unformed root are less capable of impact under the pressure of compression and bending. The system exhibits a greater resistance at 2.8 times to the compression of the Pzi than the bend of Pyi. The absence of contact contributes to the mobility of the system at 1.5 times.

The pathogenetic factors that influence the rigidity of the splint fixation on the injured teeth have been identified including a degree of root formation, the direction of the force impact, the position of the splint on the crown of the tooth, the presence of contact between adjacent teeth.

Keywords: *teeth trauma, tooth injury, dental trauma, tensely-deformed state, biomechanical system, maxilla, final elements method, teeth, splinting construction.*

Introduction. The issue of making an option of a fixation method in case of dental traumatic injuries is still relevant at present, especially in children of different age [7, 13].

It is nearly impossible to study and assess fixation rigidity of splinting structures of the injured teeth conducting primal full-scale experiments in children. Clinical evaluation used for this objective is not enough to determine fixation period and the conditions that make it less strong. Therefore, the method of mathematical modeling based on the fundamental principles of the mechanics of a solid deformed body enables to reproduce the mechanical "behavior" of the "dentition-splint" system with high precision; besides that, it allows to define the conditions affecting the rigidity degree applying computer technology. Currently, computer modeling combined with experimental methods of studying tensely-deformed state of biomechanical systems are the most informational sophisticated tools for both planning surgical operations as well as identification of an opportunity and the way to apply fixing devices [6, 11].

The Final Element Method (FEM) is well adapted to the complex geometry of the maxillofacial tissues. Its first use in the field of dentistry was conducted by Thresher and Saito, 1973 [12]; Takahashi et al., 1980; Moss et al., 1985; Kawasaki et al., 1987. They were mostly concerned with orthopedic dentistry [8-10]

To plan surgical interventions in the area of the middle zone of the face, a standardized reproducible loading pattern of the upper dentition has been developed; it adequately reflects the pressure of the lower teeth onto the upper ones in the central occlusion and can be used to make computer simulation models [1, 3, 11]. These studies were carried out using data of computed tomography of adults and reproduced models of the biomechanical system of the formed dento maxillary appliances [3, 6, 14]. As for the age aspect, there are no such studies.

The objective of the study is to determine the optimal position of the splinting construction of maxillary dentition of a child at mixed occlusion depending on the root formation and dual directions of functional load of the teeth.

Materials and methods. The object of the study is three-dimensional computer models of the biomechanical system (BS) of the maxilla with a splinting system for dentition fixing. To meet the targets, models of tensely-deformed state (TDS) of the maxilla BS with splinting structures of the dentition have been made; the methodology and algorithm of imitational mathematical modeling of the BS TDS methods have been used by means of CAD/ CAE and computed tomography (CT) data.

Reproduction of the dimensional geometry of the biological object of the maxilla with teeth was carried out using a CT scan data of a 12-year-old child.

The porous, heterogeneous structure of bone tissue has been approximated by cortical and spongy layers; for dental models, layers of enamel, dentine and periodontal ligament have been distinguished obtained from CT images in accordance with Hounsfield values [13].

Reproduction of a three-dimensional solid model of the maxilla with teeth and a splint has been made in the CAD package CATIA.

The assessment of the results' adequacy of computed mathematical modeling of the tensely-deformed state of biomechanical systems was carried out by checking the completeness and correctness of the input data of a discrete model, the correlation of calculated forces, tension and deformation with empirical and literature data [2].

According to the terms of the problem, the load models were represented by vectors of unit forces as well as the qualitative characteristics of displacement and stress fields were established.

Research results. Within the set task, the geometry of the maxilla of a healthy child with a symmetrical arrangement of 13,12,11,21,22,23 teeth has been simulated (Fig. 1).

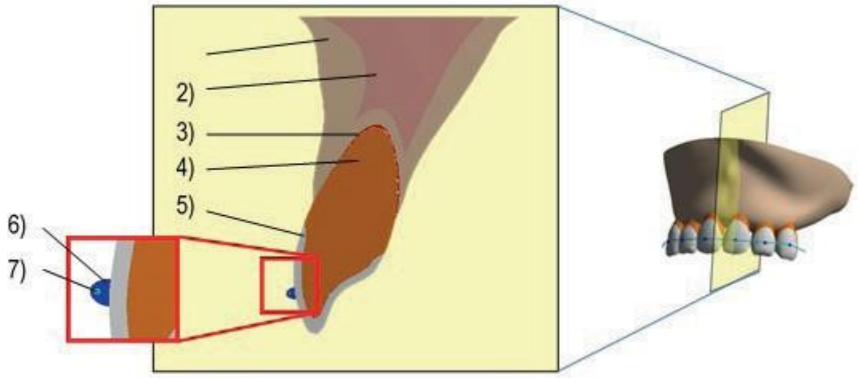

Fig.1. Solid-state computer biomechanical model of the maxilla with the splinting construction of dentition 1) cortical bone; 2) spongy bone; 3) periodontal ligament; 4) dentin; 5) enamel; 6) glue; 7) steel wire.

Three cases of the splint arrangement on the teeth were simulated - the crown of the tooth was conventionally divided into three equal parts in height. The position of the splint in the upper third of the crown (closer to the neck of the tooth) was taken as the I-st, the position of the splint in the middle of the crown of the tooth (correspondingto the equator) was taken as the II-nd;). The root length was determined as 100 % in completely formed teeth and 70 % in the teeth with incomplete formation of the root (permanent teeth), or (in temporary teeth) where physiological resorption has begun (Fig. 2).

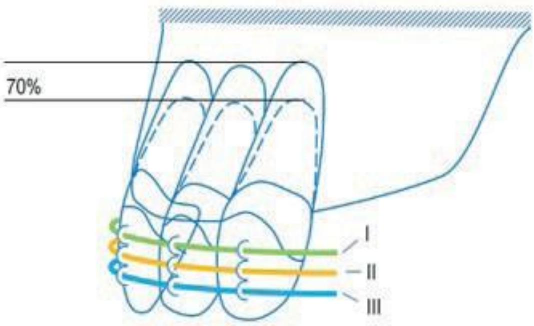

Fig. 2. Schematic representation of the studied parameters of the biomechanical system model of the maxilla with three options for the arrangement of splinting structures (I – top, II – middle, III – bottom) and two options for the length of the dental roots (100 % and 70 %).

Each biomechanical model of the maxilla with the splinting structures of the dentition was a collection of 27 structural elements (Fig. 2), for which rigid contact conditions for adjacent bodies were formed in the CAS software package ANSYS Workbench in semi-automatic mode. To study the influence of contact conditions between the teeth on the rigidity of the biomechanical system, models with contact and without it between adjacent teeth were additionally created.

For all biomechanical systems, final element sampling was carried out in semi-automatic mode using contact and 10 node pyramidal 3D SOLID187 final elements (Fig. 3).

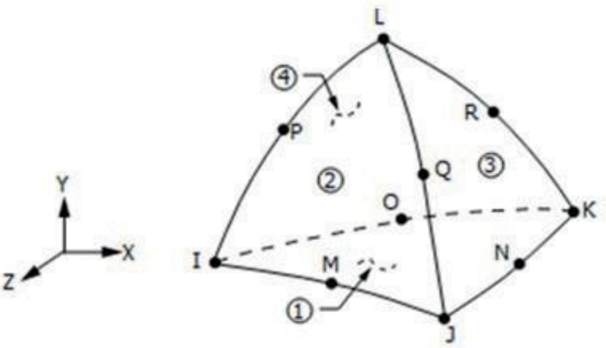

Fig.3. The schematization of the 10-node CE SOLID 187 high order 3D, which is used to simulate irregular grids [15].

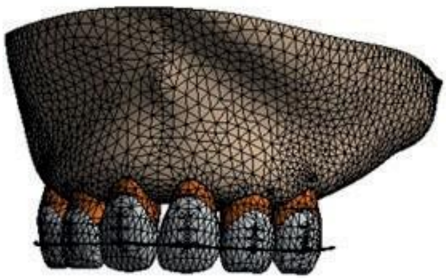

Fig.4. Three-dimensional final element model of the biomechanical system of the maxilla with the splinting construction of dentition (NN: 165418, NE: 78752)

On the average, each final element model accounted for 165,418 nodes and 78,752 pyramidal final elements (Fig. 4).

The isotropic mechanical properties of materials of structural elements of the biomechanical system obtained according to literature data [4, 5] are presented in Table 1, where the elastic modulus of the first type (tensile modulus) is a physical quantity that characterizes the elastic properties of isotropic substances. Elastic modulus under stretching is the ratio of the normal stress to the corresponding linear strain over the linear stress state to the proportional line. Poisson's ratio is the ratio of the relative transverse deformation to the relative longitudinal deformation that characterizes the elastic properties of the material.

Table 1

Models of materials of the biomechanical system of the maxilla with the splinting construction of the dentition

Material name	Elastic modulus E, MPa	Poisson's ratio ν
Cortical bone	10000	0.25
Spongy bone	1000	0.3
Periodontium	35	0.47
Dentine	18000	0.28
Enamel	43400	0.3
Splint	193000	0.31
Glue	4250	0.3

In this study, two extreme physiologically possible variants of the directions of functional force loading of teeth have been reviewed for models of biomechanical systems of the maxilla with splinting constructions of the dentition. The direction of the force vectors' action has been determined by six local coordinate systems located on the corresponding parts of the teeth. The loads are represented by "compressing" Pzi and "bending" Pyi force vectors (Fig. 5).

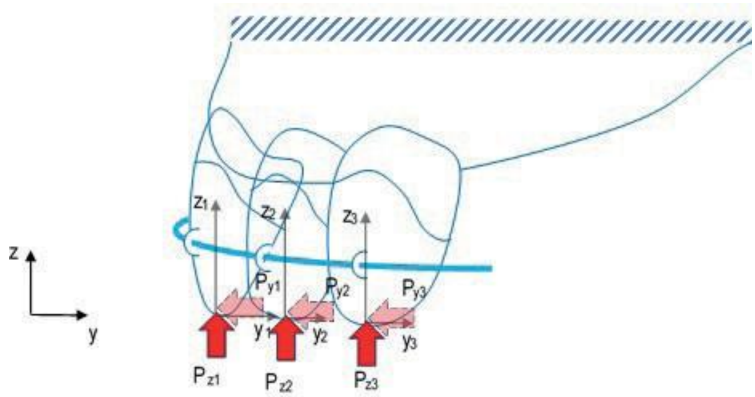

Fig.5. Load patterns of the biomechanical system of the maxilla with splinting construction of the dentition.

For this study, the total bite force was taken as 1. The load models were characterized by relative values of the efforts calculated using Agapov's weights coefficient presented in Table 2.

Totally, 24 models with a combination of parameters were made and investigated: the lengths of dental roots 100 % and 70 %, 3 variants of splint arrangement, 2 variants of contact conditions between the teeth and the vectors for compression and bending loads.

Table 2

Distribution of efforts onto the teeth

Tooth number	Agapov's weights coefficient	Coefficient of effort onto the tooth
1	2	0.08
2	1	0.04
3	3	0.12

The results of experiments' calculations of the maximum values of movements of completely formed teeth models concerning the compression and bend have shown the dependence of the splint fixation rigidity on these factors (Table 3).

Table 3

The maximum values of the movements of the biomechanical system "dentition splint" models having completely formed dental roots under load on the list (Pzi) and in the bending (Pyi).

	Maximum values of teeth movements u, mm * 10^{-5}			
	Load P_{zi} (compression)		Load P_{yi} (bend)	
Position of the splint	With Contact	Without contact	With Contact	Without contact
I - upper	3.1685	4.8204	8.9006	10.7930
II – middle	3.1693	4.8291	8.8974	10.7890
III - lower	3.1697	4.8346	8.8941	10.7850

In case of compression load (Pzi) the level of overlapping splint structure on the crown of the injured tooth having the full length of the root in case of the contact between adjacent teeth almost does not affect the alteration of the maximum value of displacement fields: I – upper position of the splint – 3.1685x10-5 mm, II – middle position – 3.1693x10-5 mm, III – lower position of the splint – 3.1697 x10-5 mm. Providing that there is no contact between the adjacent teeth under the compression load (Pzi), the mobility of the system increases: in the upper position of the splint – 4.8204x10-5mm, average – 4.8291x10-5 mm and in the lower – 4.8346x10-5 mm. In the case ofbending load (Pyi) the maximum values of displacements of teeth having full root length are the smallest on condition of contact between adjacent teeth when applying the splint in the lower position of the tooth crown – 8.8941x10-5 mm, and it gets increased at medium – 8.8974x10-5 mm and upper positions – 8.9006x10-5 mm (Fig. 6).

If there is no contact between the adjacent teeth, the indicators gradually increase from the lower position of the splint – 10.7850x10-5 mm, to the middle –10.7890x10-5 mm and the upper one – 10.7930x10-5 mm when to act on the bend (Pyi).

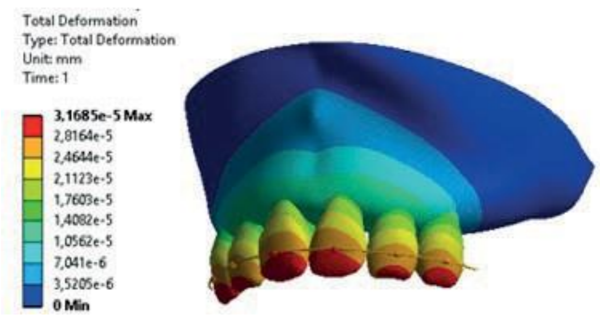

Fig.6. Fields of movements' distribution of the biomechanical system of the maxilla with splinting structures of the dentition in compressive Pzi load, lower position of the splint and 100% length of the root of the tooth.

The results of calculations of the maximum displacements of dental models that have 70 % of formed roots have shown the dependence of the rigidity of the splint fixation on the contacts between the teeth, the action of compressive and bending load vectors and 3 levels of splint positioning on dental crowns (Table 4).

Table 4

The maximum values of the models' displacements of the biomechanical system of the maxilla with teeth having 70 % of formed roots and the splinting construction in compression load (Pzi) and the bend (Pyi).

	Maximum values of teeth movements u, mm* 10^{-5}			
	Load P_{zi} (compression)		Load P_{yi} (bend)	
Position of the splint	With Contact	Without contact	With Contact	Without contact
I - upper	3.6611	5.7631	10.5830	13.3470
II – middle	3.6598	5.7728	10.5770	13.3430
III - lower	3.6579	5.7914	10.5720	13.3390

When fixing teeth with an unformed root (70 % of the length) and the existing contacts between adjacent teeth, the reduction of the maximum value of displacement fields under compression load (Pzi) is from 3.6611 x10-5 mm at the top position of the splint to 3.6598 x10-5 mm – middle and 3.6579 x10-5 mm at the bottom. The lack of contact between adjacent teeth adds mobility to the system: in the upper position of the splint – 5.7631x10-5 mm, the middle – 5.7728x10-5 mm, in the lower – 5.7914x10-5 mm. Teeth with an unformed root (70 % of the length) and the existing contacts between adjacent teeth, show less capacity under the influence of the load in the bending (Pyi). Thus, the maximum values of tooth movements when applying the splint in the lower position of the injured tooth constitute 10.5720 x10-5 mm, the average – 10.5770 x10-5 mm, and in the upper position – 10.5830 x10-5 mm. The lack of contact between adjacent teeth reduces the stability of the system: from the lower position of the splint – 13.3390x10-5 mm, to the middle –13.3430x10-5 mm and the upper one – 3.3470x10-5mm.

A combination of parameters was determined due to experimental calculations of the maximum displacements of the biomechanical system modules of the maxilla with the splint structure of the dentition under compressive (Pzi) and bending (Pyi) load, at which the system showed the least stability. This is a biomechanical system with a geometry model of 70 % of the tooth root length, without contact between adjacent teeth and in case of the bending load vector Pyi. To define the limit values of the indicated most unstable BS, the modeling of the tensely-deformed state was made with the indicators of the functional values of the loads onto the teeth, based on PΣ = 800 N for the entire jaw.

The results obtained have shown that in such conditions the largest total deformation occurs in the lower third of the crowns of central incisors and canines – 5338.7 x10-5 mm, the smallest – in the middle part of the crowns of lateral incisors and cervical areas of central incisors and canines – 2372.8 x10- 5 mm (Fig.7).

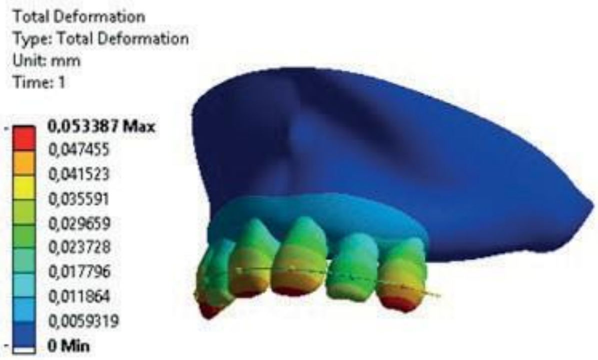

Fig.7. Distribution fields of the biomechanical system displacements of the maxilla with a splint construction of dentition in the bending Py loading, lower position of the splint and 70 % of dental root length, under the action of functional loads.

Discussion. Maximum values of teeth displacement are presented in very small absolute numbers-thousands shares of millimeters. Such numbers are not essential in themselves, they are important as a material to detect and analyze behavior patterns of the biological system while making a mathematical modeling of the tensely-deformed state depending on the input data and the application of the unit effort vector. That is, having revealed this pattern we can calculate the stability rate of fixation system of the injured teeth in this or that clinical case dependently on the area of splint application on the dental crown taking into account physiological masticatory load made onto it and the length of the root.

The rigidity analysis of the splinting construction depending on its application extent on the crown of the injured tooth having complete length of the root as well as a contact between the adjacent teeth, provided that there is (Pzi) compression load has shown that the system is more steady if to apply a splint on to the upper third ofthe crown: compared to the mid position by 0.0008x10-5 mm and the lower one by 0,0012x10-5 mm. The mobility of the biological system enhances at 1.5 times in the case of no contact between the adjacent teeth under the load made in compression (Pzi). The steadiest indices were obtained at the top position of the splint: in comparison with the mid position by 0.0087x10-5 mm and the lower one by 0,0142x10-5mm. If to compare the system with evident contacts between the teeth, maximum values of displacement is greater: at the top position of the splint by 1.6519x10-5 mm, in the middle – by 1,6598x10-5 mm and in the lower one – by 1.6649x10-5 mm.

Under the pressure made in the bend (Pyi),the maximum values of teeth displacement while applying the splint into the lower position of the injured tooth with complete length of the root and provided that there are aproximal contacts are less by 0.0033x10-5 mm than in case of the splint positioning in the middle of the crown by 0.0065x10-5 mm – at the neck of the tooth, therefore, the system is more stable if the splint is fixed in the area of the lower third of the dental crown. Such alteration pattern of maximum values of teeth displacement fields under the pressure made in the bend (Pyi) has been noted in case of having no contact between the adjacent teeth if to apply the splint in the lower position: by 0.004 x10-5 mm less than in the position of the splint in the middle of the crown and by 0.008x10-5 mm – at the neck of the tooth, that is the system is more steady in the lower positioning of the splint. The absence of contacts between the adjacent teeth under the pressure applied in the bend (Pyi) provides more mobility to the system on the average of 1.21 times independently on the extent of the splint application.

Comparative analysis of maximum values'indices of dental displacement of biomechanical system having the complete lenth of the root depending on the type of load made onto the injured tooth has demonstrated that BS identifies higher resistant capability in compression(Pzi), than in the bending(Pyi) on the average at 2.8 times. In case of the contact between the adjacent teeth, this ratio constitutes as 1:3 on the average. Provided that there is no contact between the adjacent teeth this index decreases up to 1:2.2. It indicates that the system's steadiness lowers under compressive force (Pzi) if aproximal contacts are absent.

It has been found out that the system becomes more stable while applying the splinting construction in the area of dental crowns' equator in case of pressure made in compression (Pzi) and in the bending (Pyi) on the crown of the injured tooth having complete length of the root as well as in the presence or absence of contacts between the adjacent teeth.

While fixing teeth having an unformed root (70 % of length) and evident contacts between the adjacent teeth, higher stability of systems has been detected if to apply the splint onto the lower third of the crown: compared to the mid position by 0.0019 x10-5 mm, and the upper one -by 0.0032 x10-5mm. Under the pressure made in compression (Pzi) absence of contact between the adjacent teeth adds some mobility to the system at

1,6 times on the average. Furthermore, mobility of the splinting construction increases from upside down: the difference of maximum values of displacement between the upper and middle positioning of the splint is 0,0097 x10-5 mm, the upper and lower one- 0,0283 x10-5 mm. Compared to the system with evident contacts between the teeth maximum values displacement is bigger: at the top position of the splint by 2.102 x10-5 mm, the middle one – by 2.113x10-5 mm, and in the lower position – by 2.1335x10-5 mm.

The tendency towards the decrease of resistance capability under the pressure made in the bending (Pyi) is kept even in teeth with an unformed root (70 % of the length) and in case of presence or absence of the contact between the adjacent teeth. Consequently, provided that there is contact, the system gets the most steady while applying the splinting construction in the lower third of the crown: in relation to the middle position by0.005 x10-5 mm, and the upper one – by 0.011x10-5 mm. The comparison of the influence of the efforts' vectors in compression (Pzi) and in the bending (Pyi) has revealed that the maximum values rise of the fields of dental displacement occurs under pressure made in the bend (Pyi): in the upper position of the splint by 6.9219x10-5 mm, in the mid one – by 6.9172x10-5 mm, and the lower position – by 6.9141x10-5 mm. So, under these conditions, the system is more stable if to apply the splint in the area of the cutting edge of the dental crown .If there is no contact between the teeth, it adds mobility to the system at 1.276 times on the average in contrast to the presence of contacts: at the top position – by 2.764 x10-5 mm, the mid one – by 2.766x10-5 mm and its lower position – by 2.767x10-5 mm. Its highest stability the system shows in the lower position of the splint: in relation to the mid position by 0.004 x10-5 mm, and the upper one – by 0.008x10-5 mm.

Under the conditions of teeth fixation having an unformed tooth (70 % of the length) depending on the type of load, the indices' analysis of maximum values displacement has confirmed that the system demonstrates its higher resistance capability in compression (Pzi) than in the bending (Pyi) almost at 3 times. Having a contact between the adjacent teeth, the ratio of displacements under the action in compression (Pzi) and bend (Pyi) is 1:2.8, while in case of contacts' absence, it constitutes 1:2.3. Correlations of compression (Pzi) to bend (Pyi) is similar both in the teeth possessing complete length of the root as well as formed roots up to 70% of the length.

It has been identified that the system gets the highest steadiness when applying the splinting construction in the lower third of the crown under the pressure made in compression (Pzi) and in bending (Pyi) of the injured tooth crown with 70 % of the root length, formed or resorption tooth to1/3 and the presence of contacts between the adjacent teeth. The system is more stable while fixing the splint in the area of the dental crown middle provided that there are no aproximal contacts.

Teeth with an unformed root in contrast to formed one demonstrate less resistance capability under the influence of load in compression (Pzi) both if there are contacts – at 1.15 times as well as they are absent –at 1.19 times. Under the pressure made in compression (Pyi), the same tendency has been noticed: in evident contacts between the adjacent teeth – at 1.18 times, and in case of no contact – at 1.23 times.

It has been established that tension occurring in structural elements of the biomechanical system does not exceed bounded values, that is, they have no threat to the integrity of osseous tissue and dental structures in accordance with the data of the tensely-deformed state (TDS) modeling, the most unsteady BS with a geometric model of 70 % of the dental root length, having no contact between the adjacent teeth and under the action of the bending vector Py, in functional load.

Conclusions. Computed modeling of the biomechanical system of the maxilla with the splinting construction of dentition enables to investigate in details the effect and significance of geometric parameters as well as the conditions of loads on the tensely-deformed state and rigidity of the biomechanical system.

1. Pathogenetic factors which affect the rigidity of the splint fixation on the injured teeth have been determined. They include:

- the degree of root formation (teeth with an unformed root by 70 % are les resistant under the pressure made in compression and in bend);
- the direction of the force impact (the system shows higher resistance in compression Pzi, than in the bending Pyi at 2.8 times);
- the presence of contact between the adjacent teeth (absence of contact adds mobility to the system at 1.5 times);
- the rate of the splinting construction application.

2. The rate of the splinting construction application is identified in the area of equator of dental crowns under the pressure made in compression (Pzi) and in bend (Pyi) onthe crown of the injured tooth with complete length of the root as well as the presence or absence of contacts between the adjacent teeth. In case of roots formation by 70 % of the length and evident contacts between the adjacent teeth, the rate of the splinting construction application are observed in the lower third of the crown, if there is no contact between the adjacent teeth, the system is more stable in the middle positioning of the splint.

3. It has been determined that there is no critical overload threat to the structure of the tooth under the physiological load onto the "dentition-splint" system that could result in the impairment of its integrity.

Conflict of interest. All the authors declare that they have no conflict of interest.

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