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ORIGINAL ARTICLE

STUDY OF THE STRESS-STRAIN STATE OF THE MAXILLA DURING ORTHODONTIC TREATMENT OF DENTOGNATHIC DEFORMATIONS IN CHILDREN WITH CONGENITAL CLEFT LIP AND PALATE

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ABSTRACT

The aim: To create a three-dimensional simulation mechanical-mathematical model of the biomechanical system "Orthodontic appliance-maxilla", to study peculiarities of the stress-strained state of the maxilla.

Materials and methods: A simulation model of the biomechanical system "Orthodontic appliance-maxilla" was created using computed tomography (CBCT) data. Mathematical modeling was used to determine the stress-strain state of the simulation model.

Results: The patterns of changes in the stress state were determined and the values of deformation displacements in the structural elements of the biomechanical system "Orthodontic appliance-maxilla" were determined under a force stress of the orthodontic device with an amplitude of 50 N.

Conclusions: Simulation computer modeling of the stress-strain state of the "Orthodontic appliance-maxilla" system showed that activation of the kinematic mechanism of the appliance with a force of 50 N causes the emergence of a complex stress-strain state of bones. When the orthodontic appliance is activated, there is an asymmetry in the distribution of stresses by Mises between the right and left sides both for the appliance itself and for the maxillary bone tissue.

KEY WORDS: system "Orthodontic appliance-maxilla", distribution of stresses

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INTRODUCTION

The development of a pathological occlusion is facilitated by numerous etiological factors, which affect the child's craniofacial development [1, 2]. Defects in jaw development, in particular, largely determine the occlusion and the condition of the dentition. According to statistical data, 400-500 children in Ukraine are born each year with various types of congenital CLP [3-5], among which almost 94% of cases have dentognathic deformations [3, 5-9]. The variety of clinical manifestations of malocclusion in children with congenital CLP contributes to the development and implementation of new methods of their diagnostics and treatment [9, 10].

Orthodontics is a branch of dentistry, which is deeply connected with engineering and biomechanics [11]. In recent decades, scientists thoroughly studied the peculiarities of the mechanical interaction of orthodontic devices and biological tissues using the methods of mechanical and mathematical modeling. For example, they investigated the issues of the shape of dental arches during orthognathic occlusion [12], mechanical and mathematical modeling of the process of orthodontic treatment of dentognathic deformations using pre-orthodontic trainers [13], the process of treatment of dental arch defects [14], tooth rotations [15], open occlusion [16], etc. Other studies include investigations of orthodontic forces in devices in the treatment of mesial occlusion [17] and sagittal anomalies of occlusion [18]. The effect of the forces applied to the tooth during orthodontic treatment after 3D scanning of the oral cavity was evaluated on geometric models [19].

The works of scientists outline a number of problems of computer modeling of biomechanical systems based on CBCT data [20, 21], analysis of a simulated three-dimensional model of the system "Bone tissue-dental implant-suprastructure" [22], biomechanical interaction in fixed partial prostheses [23], simulated computer modeling in maxillofacial surgery [24, 25], a study was conducted on the development of three-dimensional (3D) modeling of finite-elements for predicting tooth movement in the treatment of occlusal deformities [26] and diastema [27], three-dimensional monitoring

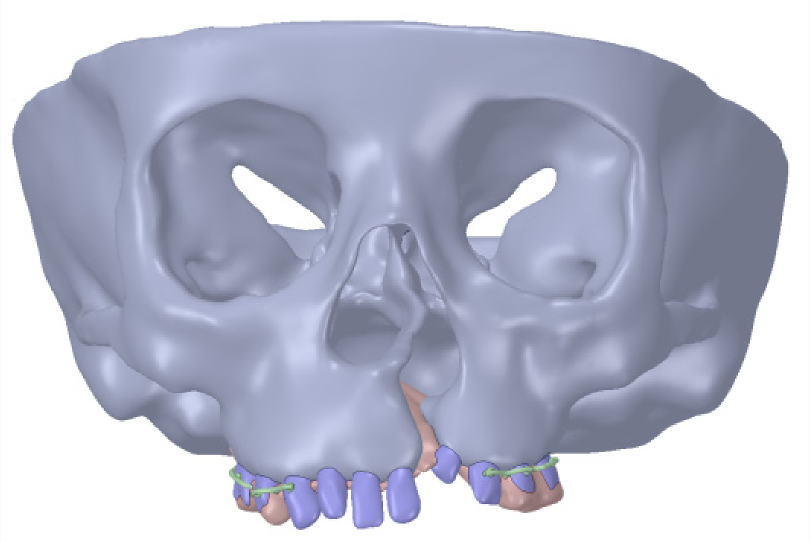

Fig. 1. Imitation model of the maxilla in a child with congenital unilateral CLP

Fig. 2. A sample of a removable orthodontic appliance used in the orthodontic treatment of a patient with a mixed dentition period with congenital unilateral CLP

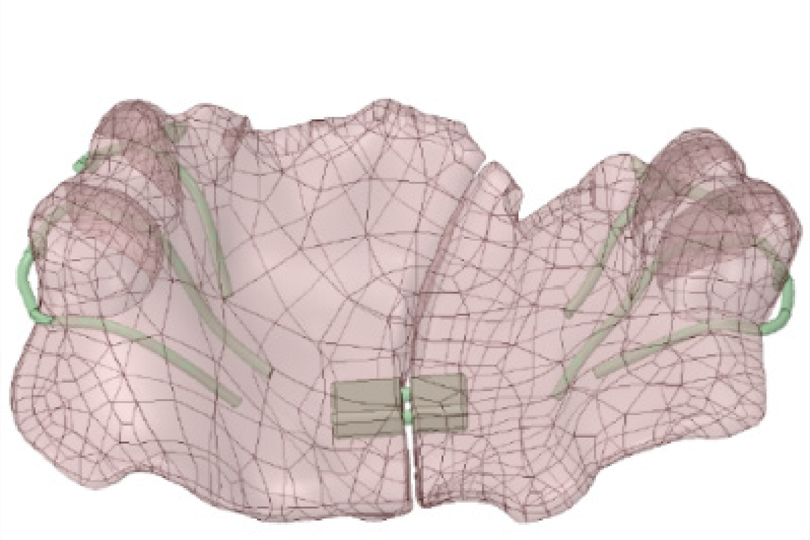

Fig. 3. 3D simulation model of the orthodontic appliance

of root movement during orthodontic treatment was described [28]. A mathematical model was developed for assessing the intensity of the force on elements of the bracket system [10]. Despite such a large number of studies on biomechanical systems in orthodontics, there are no studies of the stress-strain state of the maxilla in children with congenital CLP during orthodontic treatment.

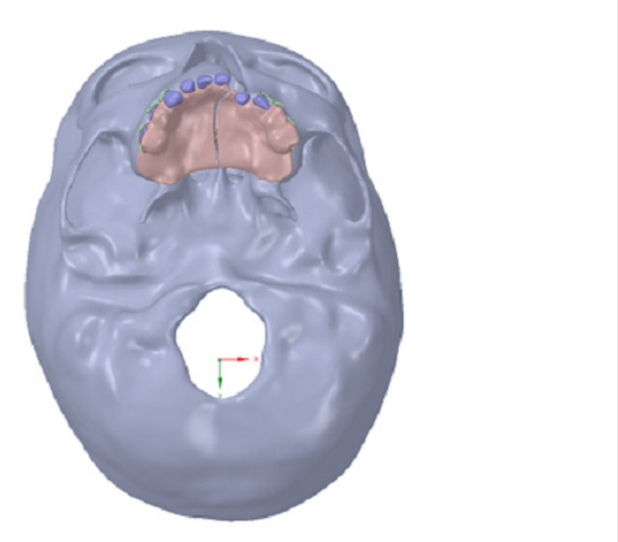

Fig. 4. Imitation model of the maxilla in a child with congenital unilateral CLP with an attached orthodontic device

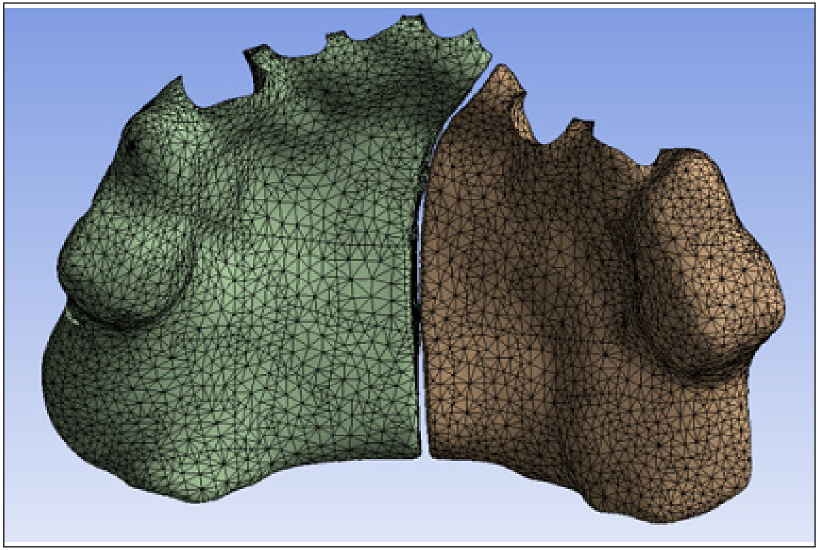

Fig. 5. Discrete model of an orthodontic appliance

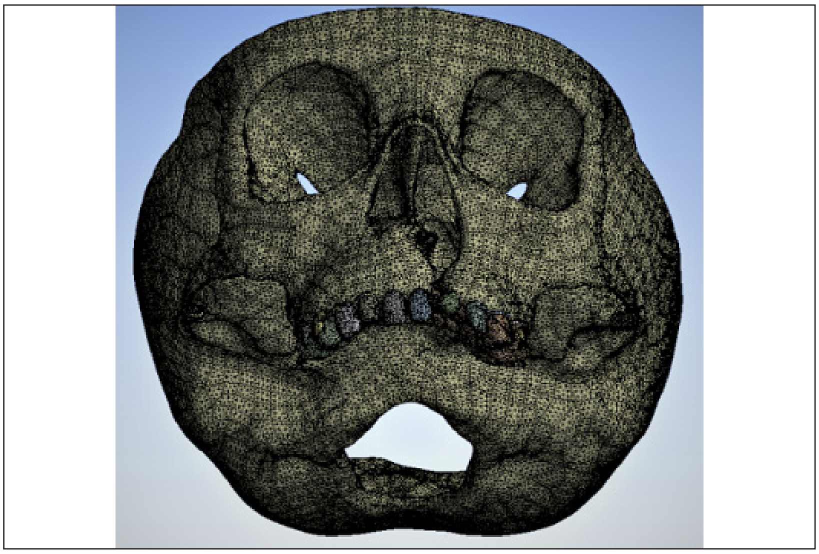

Fig. 6. Discrete model of the maxilla of a child with congenital unilateral CLP with an attached orthodontic device

THE AIM

To create a three-dimensional simulation mechanical-mathematical model of the biomechanical system "Orthodontic appliance-maxilla" in the course of orthodontic treatment of a patient in the mixed dentition period with congenital unilateral CLP, to study peculiarities of the stress-strained state of the maxilla under the action of static loads caused by the activation of the orthodontic appliance.

Table I. Models of materials of the biomechanical system

Structural elements	Yung's module, E, MPa	Poisson's ratio, ν	Strength limit
Cortical layer of maxillary bones	12650	0,25	120
Cancellous layer of maxillary bones	470	0,27	8
Metal retainers (clasps)	200000	0,3	640
Base of the orthodontic appliance	2500	0,3	80

Table II. Maximum equivalent by Mises stresses in the elements of the system "Orthodontic appliance-maxilla", permissible stresses and safety factors for the case of a quasi-static load

Structural elements of the biomechanical system	$\sigma_{екб}$ equivalent stresses, MPa	$\sigma_{в}$, strength limit, MPa	[σ], permissible stresses, MPa	η, safety factor
Maxillary bones	10.3	120	80.0	7.8
Orthodontic appliance	5.8	80	53.3	9.2
Metal retainers (clasps)	1.3	640	426.7	252.8

MATERIALS AND METHODS

The biomechanical behavior of the maxilla of a patient with unilateral CLP during orthodontic treatment was studied in a model experiment using the finite-element method. During the experiment, a simulation computer model of the stress-strain state of the "Orthodontic appliance-maxilla" system was created under static load conditions.

A three-dimensional virtual model of midface bones was built in the Mimics Medical 25.0 (Materialise, Belgium) based on CBCT data of the skull of patient P., 6.5 years old (mixed dentition period) with congenital unilateral through CLP at the stage before eliminating the residual defect of the hard palate.

CBCT data presented as a series of DICOM files were imported into Mimics software for further segmentation, during which cortical and cancellous layers of the maxilla were identified [24]. Separation of these biomechanically heterogeneous volumes of the maxilla was performed according to the radiological density of the corresponding biological structures (Fig. 1).

Digital data for the spatial geometry of a typical medical device consisting of a base, a kinematic mechanism (orthodontic screw) and metal retainers (clasps) presented in STL format were used as a model of the appliance (Fig. 2). At the same time, the simulation model was represented by two fragments of the base of the appliance connected in the area of the screw and supporting external retainers of different spatial configuration (Fig. 3).

The surface models created using Boolean operations were combined into multi-component assemblies and imported into Ansys 12.1 software (Fig. 4).

For each element of the model, volumes and a finite-element mesh were created followed by the assignment of the corresponding material properties. The discretization of all structural elements of the simulation model of the appliance was carried out in the semi-automatic mode of ANSYS 12.1 [30] using 10-nodal pyramidal finite-elements (FE) SOLID187 with 731865 nodes (Fig. 5).

A discrete model of the maxilla of a child with congenital unilateral CLP with an attached orthodontic device was built with the maximum size of finite-elements (FE) no more than 1.5 mm, which had 1 281 160 CE Solid187 with 731 865 nodes (Fig. 6, 7).

The basic mechanical properties of the bone, plastic and steel elements of the appliance were set according to results of experimental studies and available technical standards [24]. The base of the orthodontic appliance was assigned with properties corresponding to the material – plastic for the prosthesis bases. To simplify calculations, all materials were considered homogeneous, linearly elastic and isotropic.

The mechanical properties of structural elements of the simulation model are given in Table I [29].

To determine the kinematic boundary conditions, the model of midface bones was rigidly fixed blocking all types of linear and angular movements. Clasps of the orthodontic device were attached to the corresponding teeth of the maxilla using a rigid type of contact connection.

Calculated force vectors with an amplitude of 50 N were used to model the axial movements of parts of the appliance from 360° angular movements, which corresponded to one rotation of the screw. They served as initial values for determining the force loads of the corresponding surfaces in the developed calculation scheme for contacting deformable bodies of the maxilla and clasps of the orthodontic device (Fig. 8).

The total strain of the system was determined (the maximum movement of the nodes during deformation), the maximum values of the main and equivalent stresses, as well as the patterns of the distribution of stresses and strains (demonstrated in the form of color

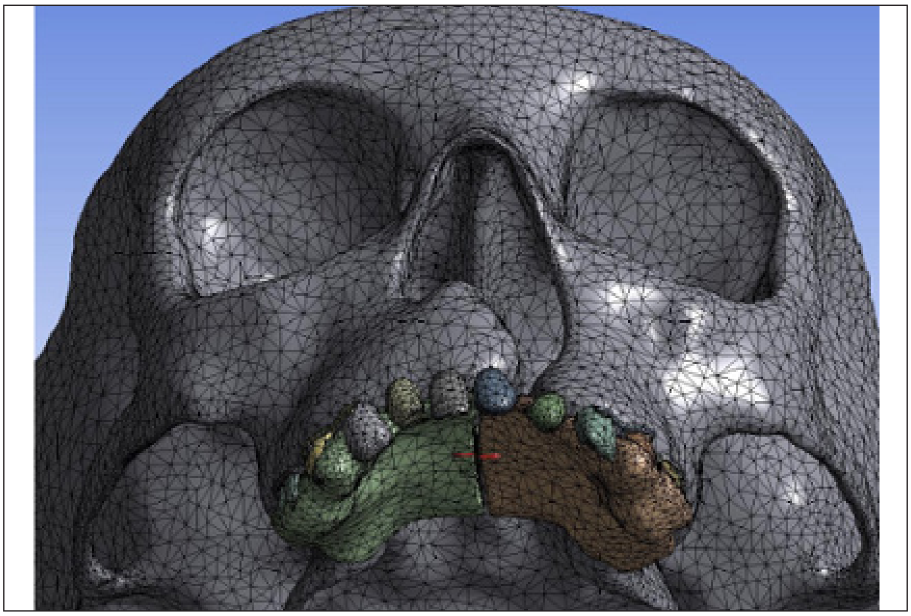

Fig. 7. Visualization of a discrete model of the maxilla of a child with congenital unilateral CLP with an attached orthodontic device

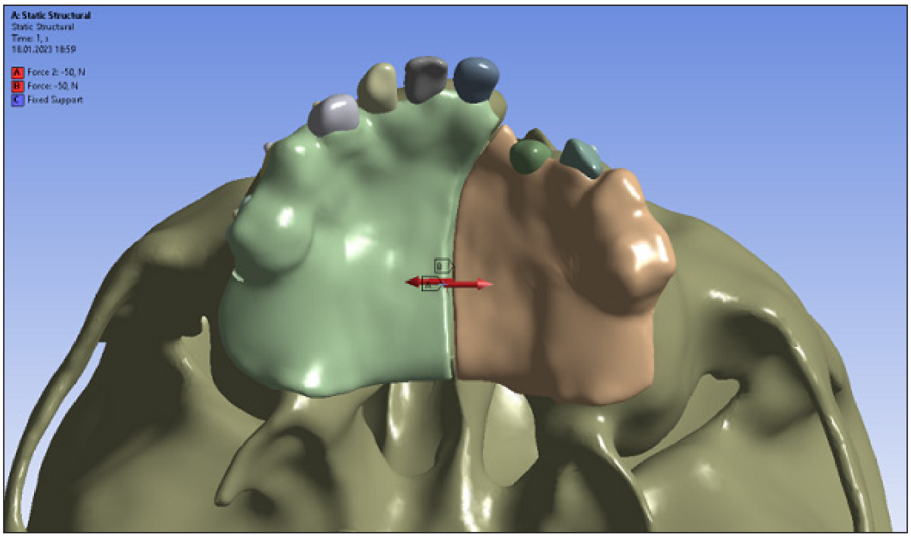

Fig. 8. Calculation scheme of the maxilla with an attached orthodontic device

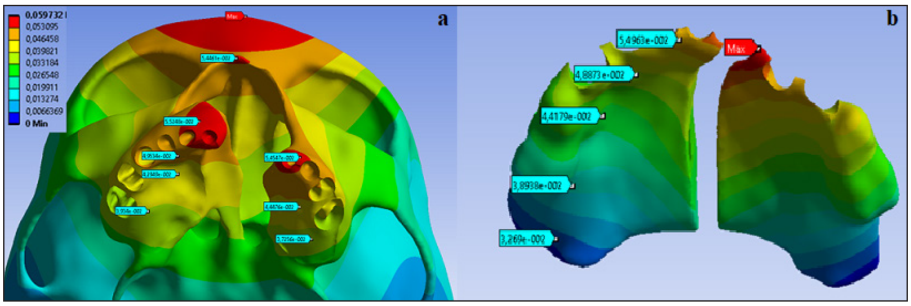

Fig. 9. Fields of displacement in mm of the maxilla (a) and the orthodontic device (b) under a force load, P=50 N

gradients or vector graphics for the cortical, cancellous layer of the bone and appliance). The strength and reliability of the "Appliance-bone" system was evaluated by the maximum value of the equivalent stresses in the structural elements and bone tissue of the maxilla by comparing them with the maximum permissible values for different types of material known from the literature.

RESULTS

The results of the numerical experiment are represented by fields of displacement (in mm) of the maxilla (Fig. 9 a) and the orthodontic device (Fig. 9 b) under a force load, P=50 N, by the fields of equivalent by Mises stresses of the maxilla (Fig. 10 a - c) and the orthodontic device (Fig. 10 d) at the specified level of force loads and the direction of movement of the

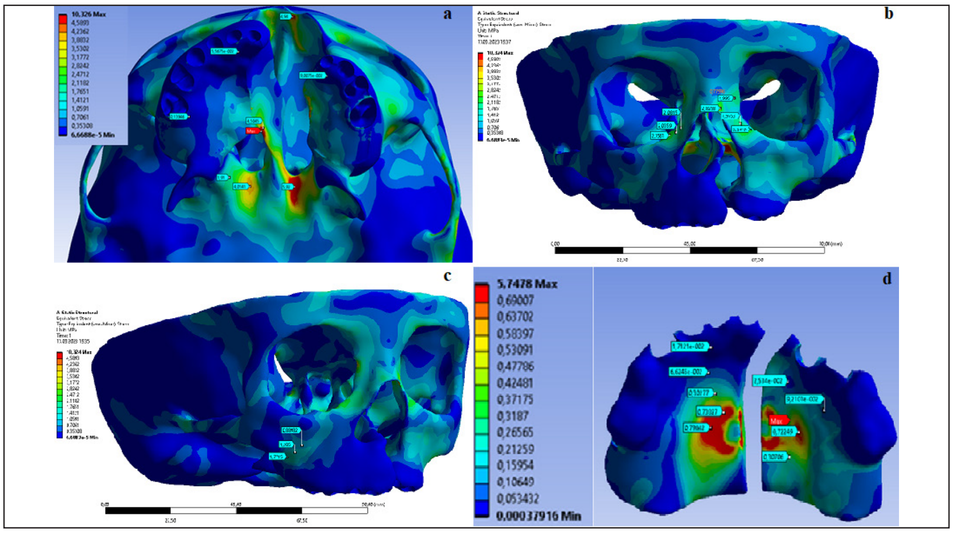

Fig. 10. Fields of equivalent by Mises stresses of the maxilla (a - c) and the orthodontic device (d) under a force load, P=50 N

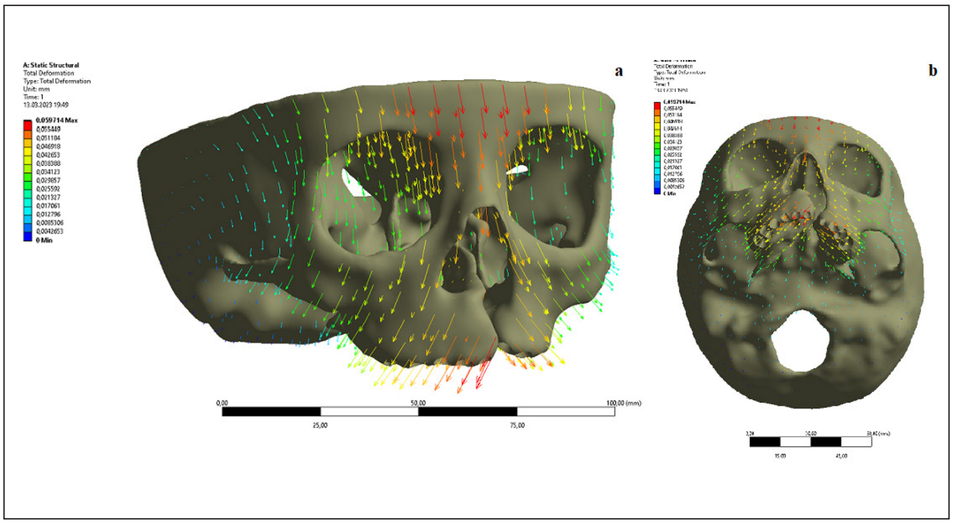

Fig. 11. The direction of displacement of the model nodes under the given conditions of the force load (a, b)

nodes of the model under the specified conditions of the force load (Fig. 11 a, b).

Analysis of the obtained data determined the magnitudes of the deformation displacements of structural elements of the biomechanical system for the given amplitude of the force load of the orthodontic appliance, which have the greatest clinical importance.

The "Orthodontic appliance-maxilla" system was in a complex stress-strained state, which implied the presence of stretching, compression, bending and torsional deformations. The maxilla underwent expansion, most pronounced in the area of the alveolar process in the cleft zone. For example, along the anterior edge of the cleft, the maximum displacements q_{max} were 0.053 mm. On the other hand, in the posterior part of the cleft, they did not exceed 0.037 mm. On the edges of the surface of parts of the appliance with a screw, q_{max} was in the range from 0.039 mm to 0.059 mm. The non-homogeneity of the deformations of the orthodontic apparatus itself was caused by the constructive location of the screw relative to the base of the device. In addition, the degree of deformation directly depended on the spatial location of the device on the maxilla.

Force loads were transmitted from the orthodontic appliance through the teeth to which it was attached on the maxilla tissue, while the extreme values of equivalent by Mises stresses in its cortical layer reached $S_{åêâ}$ = 10.3 MPa. The equivalent by Mises stresses in the orthodontic wire turned out to be quite small; their values were in the range from 0.28 MPa to 1.3 MPa.

At the same time, stress distribution in the bone tissue was not uniform: the maximum gradients of equivalent stresses were observed in the area of the osseous nasal septum, horizontal plates of the palatine bone, in the vicinity of the pterygoid-maxillary junction, in the area of the zygomatic-alveolar process and the frontal process of maxilla. Through the system of vertical and horizontal counterforces of the midface, stresses from the orthodontic appliance were redistributed and transferred to the structures of the cranial base and vault.

The greatest stresses (from 5 to 10.3 MPa) were observed in the area of the osseous nasal septum and the posterior third of the hard palate. Tensile forces capable of stimulating appositional bone growth prevailed in these zones. On the other hand, the naso-frontal and zygomatic-alveolar counterforces underwent predominant bending and displacement, and the value of equivalent by Mises stresses in the zones of their maximum concentration ranged from 1.5 to 3.5 MPa. At the same time, asymmetry in the distribution of stresses, which were 18-24% higher around the small fragment of the maxilla, was observed.

The stress distribution in the base of the orthodontic appliance was uneven; the areas around the screw took the greatest loads. The maximum gradients of equivalent by Mises stresses were observed at a distance of one third of the width of the appliance, where $S_{åêâ}$ values in these zones ranged from 0.73 MPa to 0.79 MPa, while their maximum values reached 5.8 MPa.

An approximate estimate of the strength and permissible values for this type of force loads in the elements of the biomechanical system "Orthodontic appliance-maxilla" was calculated (Table II). Permissible stresses for materials are given with a safety factor of 1.5.

The analysis showed that the safety factor η>1 was established for all structural elements of the studied biomechanical system. The bearing capacity of this biomechanical system under a force load with an amplitude of 50 N is determined by the strength of maxillary bones with a safety factor of η=7.8, which corresponds to a 360° rotation of the kinematic mechanism rod and an axial movement of 1 mm.

DISCUSSION

In view of account the data on the prevalence of congenital CLP [3-5] and the percentage of dentognathic deformations with a variety of clinical manifestations [3, 5-9], it is important to develop and implement new methods of their diagnosis and treatment. The study of the features of the biomechanical behavior of systems that include the orthodontic structure and the maxillofacial apparatus in experimental and theoretical studies to determine the rigidity of orthodontic devices is the basis of high-quality complex rehabilitation of patients with congenital defects.

Experimental and theoretical studies are based on mechanical and mathematical modeling of the stages of orthodontic treatment of dentognathic deformations [9, 10, 12-19]. The analysis of the interaction of parts of biomechanical systems, the study of the stress-strain state of the dentognathic apparatus, the study of points of resistance during orthodontic treatment, the issue of the process of treating defects of the dentition in children, tooth rotations, open bite are fully covered in modern scientific literature [10, 20-28]. Ukrainian and foreign scientists have covered the issue of the expansion of the upper jaw [13-18, 31]. However, the mentioned studies covered the spectrum of the stress-strain state of the dentognathic apparatus without congenital malformations. Taking into account the anatomic-topographical and functional features of the unfused upper jaw [3, 5, 8], the data can't be fully interpreted in children with congenital CLP.

Taking into account the specifics of dentognathic deformations in this category of patients, the question of the regularity of changes in the stress-strain state and the determination of the magnitude of deformation displacements in the structural elements of the biomechanical system "Orthodontic appliance-maxilla" under the force stress of the orthodontic device is modern and relevant.

Since scientific sources do not pay attention to this issue, the results of numerical experiments conducted for the first time in children with congenital defects of the maxillofacial area can be used to prognostication the treatment strategy using an orthodontic device of a certain configuration. Verification of the distribution of force response values of orthodontic devices in the process of their deformation allows obtaining new data on the magnitude of external loads on the jawbones.

Prospects for further research should be aimed at determining the radiological density of bone tissues of the maxillofacial area in children with congenital CLP in defined resistance zones, where the stress distribution is not uniform.

CONCLUSIONS

According to results of simulation computer modeling of the stress-strain state of the "Orthodontic appliance-maxilla" system, the activation of the kinematic mechanism of the device with a force of 50 N causes the emergence of a complex stress-strain state of the midface bones, which include stretching, compression, bending and torsional deformations. The largest displacements of the model nodes are observed on the alveolar process of the maxilla in the anterior part of the cleft, which are 30% larger than in the posterior part.

Equivalent by Mises stresses in the maxillary bone tissue are unevenly distributed. Their maximum gradients were observed in the area of the osseous nasal septum and the posterior third of the hard palate (5-10.3 MPa), the frontal process of maxilla, the zygomatic-alveolar crest", and the pterygoid-maxillary junction (1.5 to 3.5 MPa).

When the orthodontic appliance is activated, there is an asymmetry in the distribution of stresses between the right and left sides both for the appliance itself and for the maxillary bone tissue (maximum stresses were 18-24% higher on the small fragment than on the large one), which was due to the structural arrangement of the kinematic mechanism relative to the base of the device and the peculiarities of the spatial location of the device on the maxilla.

When the appliance is activated with a force of 50 N, which corresponds to a 360° rotation of the kinematic mechanism rod, the stresses in the base of the device and bone tissue do not exceed the maximum permissible values. The safety factor η is 9.2 for the device and 7.8 for the bone tissue.

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The Authors declare no conflict of interest.

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