J. Appl. Comput. Mech., 11(3) (2025) 715-737
DOI: 10.22055/jacm.2024.47055.4653

ISSN: 2383-4536
jacm.scu.ac.ir

Shahid Chamran University of Ahvaz

Journal of Applied and Computational Mechanics

Research Paper

Assessment of Maxillary Expansion Techniques by means of 3D Elastoplastic Finite Element Static Simulation

Olesya Shosheva[1], Mikhail Zhmaylo[1], Leonid Maslov[1,2], Alexey Borovkov[1], Nataliia Vishneva[3], Anastasiia Lanina[4], Andrey Yaremenko[3]

[1] Advanced Engineering School "Digital Engineering", Peter the Great St. Petersburg Polytechnic University, 29 Politekhnicheskaya str., St. Petersburg, 195251, Russia, Email: shosheva.o@compmechlab.ru (O.S.); zhmaylo@compmechlab.com (M.Z.); maslov.l@compmechlab.ru (L.M.); borovkov@compmechlab.com (A.B.)

[2] Department of Theoretical and Applied Mechanics, Ivanovo State Power Engineering University, 34 Rabfakovskaya str., Ivanovo, 153003, Russia, Email: leonid-maslov@mail.ru

[3] Department of Surgical Dentistry and Maxillofacial Surgery, Federal State Budgetary Educational Institution of Higher Education "Academician I.P. Pavlov First St. Petersburg State Medical University" of the Ministry of Healthcare of Russian Federation, 6–8 L'va Tolstogo str., St. Petersburg, 197022, Russia, Email: natalia.vishnyova@yandex.ru (N.V.); hirstom_pspbgmu@mail.ru (A.Y.)

[4] Educational and Clinical Dental Center, North-Western State Medical University named after I.I. Mechnikov, 1/82 Zanevskiy av., St. Petersburg, 196006, Russia, Email: sadis57@mail.ru

Received May 31 2024; Revised October 15 2024; Accepted for publication October 16 2024.
Corresponding author: M. Zhmaylo (zhmaylo@compmechlab.com)

Abstract. Even though numerous studies considered various approaches for maxillary expansion, there is still no consensus on which method is optimal for a patient with a particular clinical picture. The purpose of this study is to determine the optimal technique from the procedures proposed by doctors for a patient with completed facial skeleton growth. In this paper we consider four scenarios of surgical intervention, i.e., without osteotomy, midpalatal suture osteotomy, experimental osteotomy of zygomatico-alveolar ridge on the both sides of maxilla, and midpalatal suture osteotomy with osteotomy of zygomatico-alveolar ridge. In addition, two experimental appliances (one-screw expander and two-screw expander) and two positioning configurations of them (parallel to the hard palate and horizontal) are under consideration at the suggestion of the doctors. The criteria for determining the optimal technique are established in the article. Three-dimensional finite element (FE) models of skull and teeth of an adult 43-year-old patient with an ossified midpalatal suture are constructed based on the results of computed tomography, while the 3D models for the expander components are built separately and combined into the full FE system. The corresponding elastoplastic properties are adopted for the bone tissues and expander components. After proper skull fixation at the bottom, a quasi-static displacement of 0.25 mm, corresponding to quarter-turn of the control screw, is applied to the expander components to stimulate the maxillary expansion. All analyses in the paper are performed in the SIMULIA Abaqus 2021 software suite. Displacements and stresses in the bone structures of the hard palate and the appliance are obtained for all the cases studied. It was revealed that the expansion of the midpalatal suture is small in the cases without surgical intervention. A significantly greater expansion of the midpalatal suture is observed as a result of midpalatal suture osteotomy. Osteotomy of the zygomatico-alveolar ridge has virtually no effect on the value of the midpalatal suture expansion. Midpalatal suture osteotomy combined with osteotomy of the zygomatico-alveolar ridge leads to maximum expansion of the midpalatal suture. However, additional osteotomy of the zygomatico-alveolar ridge induces a proportionally greater increase in the expansion value at the dental level (by 24.8–25.8%) than at the midpalatal suture level (by 10.8–16.2%). Unlike the one-screw expander, using the two-screw expander leads to a 21.4–22.9% greater expansion of the midpalatal suture in the cases with midpalatal suture osteotomy, but increases the highly stressed regions and the magnitude of plastic strains in them. The horizontal position of the expander contributes to a more symmetrical expansion of the maxilla than positioning the expander parallel to the palate. Based on the analysis performed, we believe that midpalatal suture osteotomy might be the best scenario for surgical intervention for maxillary expansion in patients with completed facial skeleton growth. The two-screw expander is more effective in terms of maxillary expansion values, but it increases the risk of bone resorption. It is also found that providing osteotomy of zygomatico-alveolar ridge and changing the position of the expander practically does not affect the expansion state. Thus, our findings can serve as a basis for doctors deciding which scenario of surgical intervention and expander configuration would be more appropriate for a particular patient.

Keywords: Orthodontics, Maxillofacial Surgery, Osteotomy, Distraction Osteogenesis, Orthodontic Appliances, Finite Element Analysis (FEA).

1. Introduction

Maxillofacial anomalies and dentofacial disorders are the cause of physical and psychological distress for patients; treatment of these conditions remains a challenge. Maxillary constriction is an anomaly, where the transversal dimension of the maxilla is

Published online: October 31 2024

reduced. The condition is predominantly congenital [1–4]. The most common complaints of patients include misaligned or crowded teeth, difficulty in nasal breathing, difficulty in chewing food and other functional impairments [5–7].

The key treatment options for maxillary constriction or micrognathia include expansion with orthodontic appliances (distraction osteogenesis), surgical expansion (orthognathic surgeries) and surgically assisted expansion with orthodontic appliances. Distraction osteogenesis (DO) consists in stimulating the regeneration of bone and adjacent soft tissues by gradual and controlled displacement of the halves of the maxilla (separated due to the rupture of midpalatal suture or surgically) using a specialized distraction device [1, 8]. Orthognathic surgery involves a segmental osteotomy procedure, where bone segments are cut out, repositioned and subsequently fixed with customized screws and plates.

The benefits of distraction osteogenesis compared to classical surgical approaches include simultaneous expansion of surrounding soft tissues and neurovascular structures as well as potentially higher stability [9]. A number of studies have found that this method reduces surgery duration, blood loss and duration of hospital stay compared to orthognathic procedures [10, 11]. However, the total treatment times are longer with this method.

The treatment method is selected based on the age of the patient as well as the aetiology and severity of the maxillofacial anomaly.

In most cases RPE/RME (Rapid Palatal/Maxillary Expansion) has proved effective for patients with continued growth of the facial skeleton [12, 13]. This technique is based on using an orthodontic appliance that ruptures the midpalatal suture. The appliance consists of two parts connected by a screw. Each of the parts includes two metal retention arms and is equipped with an acrylic pad completely reproducing the shape of the palate. These acrylic pads form the base of the appliance. Metal bands that go around the anchor teeth attaching the appliance are located at the ends of the retentions. The parts of the appliance are spread apart with each rotation of the screw using a special key. However, this method is less effective and stable and causes various complications in patients with completed facial skeleton growth [14–16].

Adult patients with completed facial skeleton growth are treated by the SARPE/SARME technique (Surgically Assisted Rapid Palatal/Maxillary Expansion), if significant maxillary expansion is required and if the previous RPE expansion has been ineffective [12, 13]. In this case, a surgical intervention is performed before the expander is installed, generally including osteotomy of the midpalatal suture and osteotomy along the line of the lower type of Le Fort. A study reviewing SARPE in an overall sample of 851 patients found minor surgical and orthodontic complications in 187 patients (22%) [17].

A less invasive technique than SARPE is MARME/MARPE (Miniscrew-Assisted Rapid Palatal/Maxillary Expansion) where the expander is fixed to the palate by mini-screws [12]. This technique was developed to maximize the skeletal effects and minimize the dentoalveolar effects of the expansion. The technique relies on the results of radiographic and histological studies, finding that the midpalatal suture may not completely ossify even in patients with completed facial skeleton growth [18–20]. The MARPE technique as non-surgical orthodontic treatment shows results similar to those of orthognathic surgery (lower type of Le Fort osteotomy) and SARPE [21].

A new expansion technique introduced recently is called MISMARPE (Minimally Invasive Surgical and Miniscrew-Assisted Rapid Palatal Expansion), combining the positive outcomes of SARPE and MARPE [22]. The technique involves the use of MARPE expander and performing osteotomies with a minimally invasive approach under local anaesthesia with a premedication, in an outpatient setting. This approach thus provides significant maxillary expansion and reduces costs and patient morbidity by avoiding hospitalisation and the need for general anaesthesia [23].

As the range of orthodontic appliances and surgical techniques for maxillary expansion is ever-widening careful attention should be paid to studying their biomechanical aspects to determine the approach yielding the best results.

The key research methods widely employed in medical biomechanics and bioengineering, such as photoelastic analysis, animal and in vitro experiments, are excessively complex and have limited validity as well as ethical constraints [24–26]. A new rapidly evolving approach that has become the third de-facto standard as a research method along with theoretical and experimental studies is called computer-aided engineering (CAE), offering an array of tools for solving engineering problems using simulation software based on numerical analysis. The most common approach is finite element analysis (FEA), predicting an object's behavior based on calculations made with the finite element method (FEM). FEM uses a mathematical framework to partition complex systems into smaller, simpler units, i.e., the finite elements. Partial differential equations are then solved for each element individually, using computational techniques. Numerical simulation based on detailed FEA has many advantages for studies of bone structures: it is completely non-invasive, the stresses can be accurately calculated at any point of the body, the method allows to model any loading schemes depending on the clinical situation, the study can be repeated an unlimited number of times, and there are absolutely no ethical issues. The latter is ensured by obtaining informed consent from the patient whose computed tomography images are used in our study. Moreover, FEA is a non-invasive research method and reduces the number of human subjects required in early phase clinical trials.

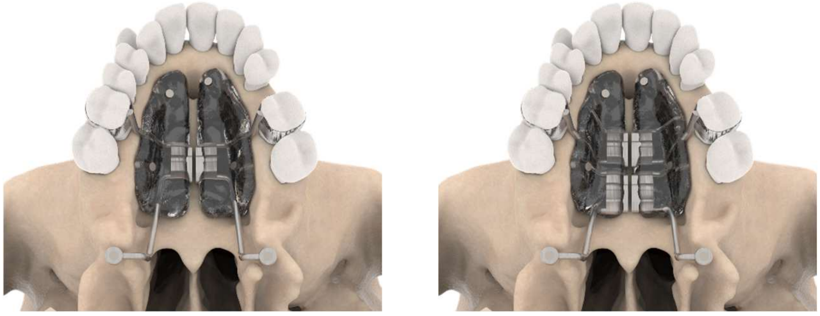
Finite element modelling and stress-strain analysis of the human skeleton are commonly used in traumatology [27–35]. This method is extremely interesting for maxillofacial surgery but is not yet widespread due to its technical complexity [36–40]. As for maxillary expansion studies generally consider the stress-strain state of craniofacial bones and teeth using different surgical techniques to eliminate the defect and/or various orthodontic devices [41–46]. However, other pieces of research have taken a different path. For examples, Priyadarshini J. et al. [47] used finite element analysis to evaluate the stress distributions along the maxillofacial sutures during RPE. Other studies use FEA to assess the influence of various parameters of the MARPE expander, such as the number, position, length and material of mini-screws, the position of the expander, and the changes in the hook length [48, 49].

Nowadays there is still no consensus on which method is optimal for a patient with a particular clinical picture. Even though numerous studies considered maxillary expansion, the accumulated clinical experience and the evidence in the orthodontic literature is insufficient in this area due to a variety of factors: types of appliances, surgical scenarios, individual characteristics of patients. Another major problem is determining the minimum extent of surgical intervention to yield satisfactory results. The main goal of our paper was to determine the optimal MISMARPE technique from the procedures proposed by orthodontics and maxillofacial surgeons for a patient with completed facial skeleton growth. The optimal technique is determined from the results of stress-strain analysis of the patient's maxillary bones by means of the criteria defined in the paper.

2. Materials and Methods

2.1. Object of the Research

The object of our research includes a skull without the mandible, a maxillary tooth row, an acrylic base, a two or four-part expander (depending on the number of expansion screws), four mini-screws and bands to be attached to the teeth (Fig. 1).



(a) (b)

Fig. 1. Object of the research: (a) with one-screws expander; (b) with two-screw expander.

(a) (b)

Fig. 2. (a) Results of the processing of the CT scan images including the mandible; (b) considered geometric model of teeth and skull excluding the mandible.

Fig. 3. Results of MSCT of the patient's head.

2.2. Construction of Geometric 3D Models of the Skull and Teeth

Geometric models of teeth and skull excluding the mandible (Fig. 2) are based on the results of multispiral computed tomography (MSCT) of the skull of an adult 43-year-old patient with an ossified midpalatal suture (Fig. 3). At the first stage of construction, CT scan images were segmented in the open-source software system 3D Slicer 5.6.2. Voxels with X-ray density values of 1250 HU and higher were selected to generate a mask of the outer surface of the cortical bone. Small local adjustments were applied to several regions, such as the nasal septum, where bone structures have extremely small thickness comparable to the voxel size. As for the mask of the outer surface of the teeth, voxels with X-ray density values of 2550 HU and higher were selected to generate it. The surface model of bone structures and teeth obtained by segmentation was exported to STL (stereolithographic) mesh format.

The geometry of the bone structures and teeth obtained from 3D Slicer was further processed in Autodesk Meshmixer 3.5.474, a free geometric modelling system. Various defects of the geometric model that appeared during segmentation were eliminated during this procedure. Important steps taken at this stage included slicing of craniofacial bones and teeth into layers with different mechanical properties using the offset command. The thickness of the cortical bone layer was chosen to be 1.0 mm. In the regions where the cancellous bone layer was less than 1 mm thick, it was assumed that cancellous tissue was absent and bone was represented only by cortical tissue of greater thickness. And the thickness of dental tissues was selected based on CT data and representative sources [50]. The periodontal ligament (PDL), a soft tissue between the teeth and the bone, was not considered in the study, since the presence of PDL would have affected primarily the stress-strain state of the alveolar bone around the teeth, which is of less interest than the stress-strain state of midpalatal suture. In addition, there are no non-invasive methods to obtain patient-specific PDL data, as CT cannot accurately represent it. Holes and cuts in the maxilla in the amount planned in the surgery were added to the geometric model at the end of this stage.

Table 1. Physico-mechanical properties of materials.

Material	Young's Modulus (MPa)	Poisson's Ratio	Yield Stress (MPa)	References
Cortical Bone	8 750	0.25	41.8	[53]
Cancellous Bone	4 660	0.25	13.6	[53]
Enamel	84 100	0.33	–	[54]
Dentin	18 600	0.31	–	[54]
Pulp	2	0.45	–	[55]
Acrylic Resin QC20	1 200	0.35	35.3	[56]
Stainless Steel X5CrNi18.10/1.4301	200 000	0.28	400	[57]
Titanium Alloy Ti-6Al-4V	113 800	0.34	950	[27]

2.3. Construction of Geometric 3D Models of the Acrylic Base, Expander, Mini-screws and Bands

Geometric models of the acrylic base and bands are built using Autodesk Meshmixer tools. The ANSYS SpaceClaim 2019.2, a direct modelling system, was also used to prepare the geometry, in particular, to build the geometric models of mini-screws and expander components. The expander model considered (Fig. 4) is a somewhat geometrically simplified model of the VECTOR® 600/620 expansion screw from SCHEU-DENTAL [51, 52].

2.4. Properties of Materials

Despite the presence of a porous microstructure in bone tissue, all materials are assumed to be homogeneous with isotropic effective properties within the current problem statement.

The structural elements of the expander are made of stainless steel, and the mini-screws are made of titanium alloy. The material for the acrylic base is heat-cured acrylic resin. The physico-mechanical properties of all materials discussed are given in Table 1.

The bone structures of the skull, including the maxilla, are divided into the outer cortical layer and inner cancellous layer (Fig. 5). The teeth, in turn, are divided into three layers: enamel, dentin and pulp (Fig. 6).

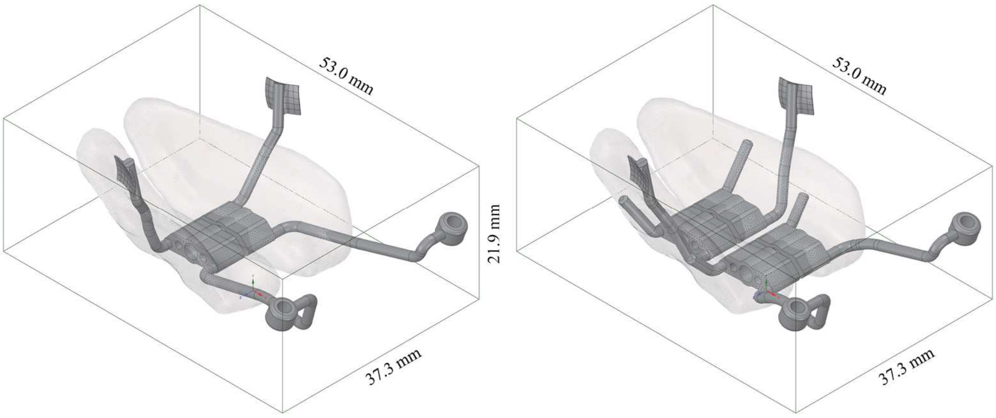


Fig. 4. Geometric model of the expander.

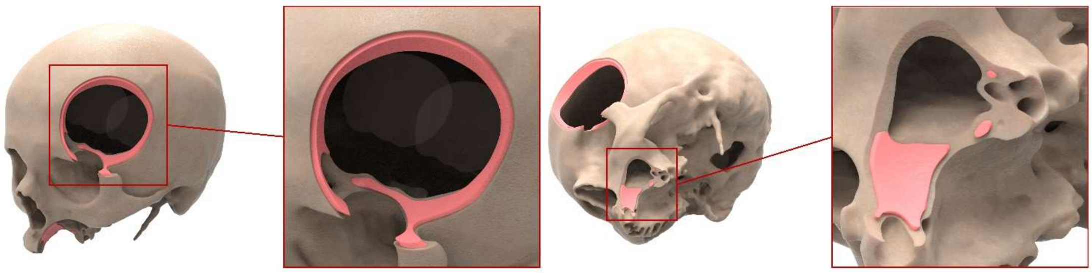
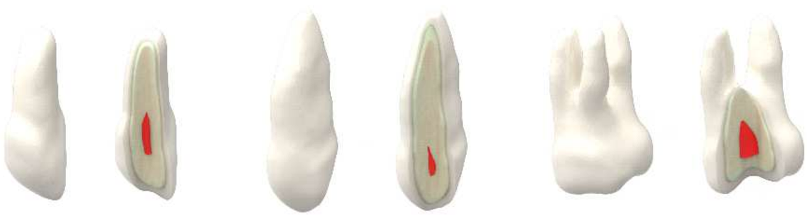


Fig. 5. Bone structures of the skull split into layers.



(a) (b) (c)

Fig. 6. (a) Incisor split into layers. (b) Canine split into layers. (c) Molar split into layers.

Faithfully describing the nonlinear behavior of bone tissue is an extremely complex problem. However, the emphasis in this study is placed on obtaining a conservative estimate for the risks of bone fracture and loss of load-bearing capacity. For this reason, we adopted a model of an ideally elastic-plastic body without hardening for bone tissue, allowing to correctly reproduce the linear segment in the behavior of the material, after which the material exhibits plastic behavior.

A model of an ideally elastic-plastic body was also adopted for all other materials of the given mathematical model, except teeth. Thus, the above materials are nonlinear to the extent that they can be made nonlinear based on the available data. The model of a linear elastic body was adopted for the dental tissues. The stress-strain state of the teeth is considered, but is beyond the main scope of our study.

2.5. Interactions

The finite element model assumes ideal linear constraints between the skull and the teeth, between the bands, the expander and the teeth, between the expander and the acrylic base, between the acrylic base and the mini-screws, between the mini-screws, the expander and the skull. In addition, the model assumes a nonlinear contact interaction between the acrylic base and the surface of the hard palate, with a friction coefficient of 0.1 (Fig. 7).

2.6. Boundary Conditions and Loads

Our goal was to evaluate the stress-strain state of the maxillary bone structures at an expansion value of 0.25 mm, which corresponds to a quarter-turn of the screw. This value represents the amount by which the appliance expands in one day.

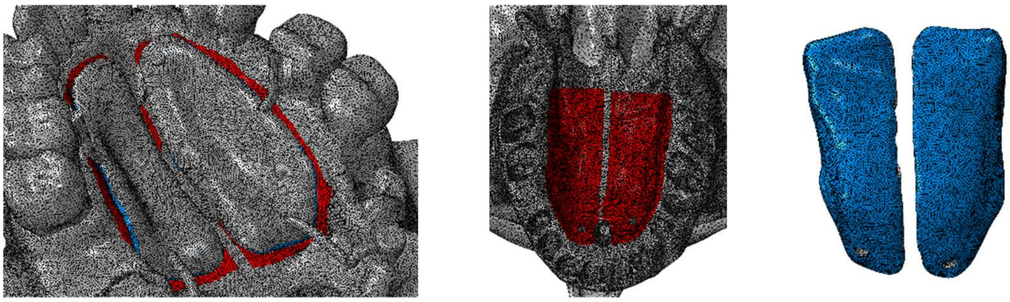
The modelled expanders consist of two halves connected by two linear guides. The position of the halves relative to each other is adjusted by means of a screw located between the above-mentioned axes. The expander halves in the model are directly linked by a connector tool, as shown in Fig. 8a. Kinematic coupling constraints are imposed in each of the halves at the centers of the axial holes to connect the cylindrical surfaces of the holes to the reference points. The pairs of reference points belonging to different halves and facing each other are linked by linear connectors, allowing relative displacement of the halves along the axes and prohibiting any other relative displacements.

A kinematic loading approach is used to simulate the process of maxillary expansion using appliances. Loading is implemented by setting the relative displacement in the connector modelling the screw. This makes it possible to directly reproduce the phenomenon of appliance expansion that occurs when a patient turns the screw.

As for the boundary conditions, all translational degrees of freedom of the nodes in the contact area between the skull and the first cervical vertebra were fixed (Fig. 8b). This boundary condition provides an increase in the stability of the problem solution and does not significantly affect the results in the maxillary region.

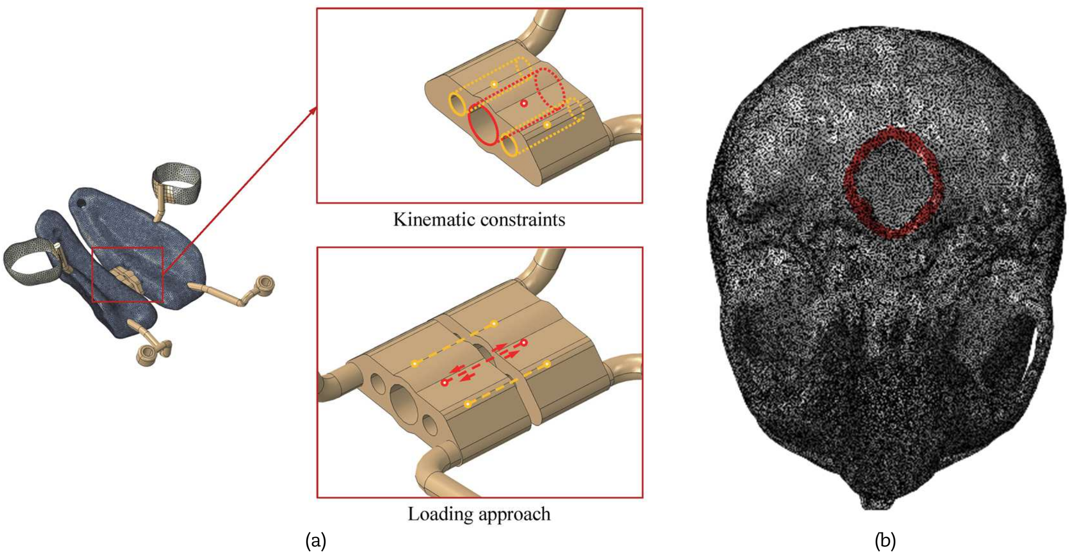
2.7. Finite Element Meshing

Altair SimLab tools were used to build finite element meshes of the skull, teeth and acrylic base. The meshes of the remaining components of the model were constructed in SIMULIA Abaqus 2021 (Figs. 9 to 12). The characteristics of finite element meshes of each of the model components are given in Table 2.



(a) (b) (c)

Fig. 7. Contact interaction between the acrylic base and the surface of the hard palate:
(a) general view; (b) contact region on the hard palate; (c) contact region on the acrylic base.



(a) (b)

Fig. 8. (a) Simulation of expansion. (b) Contact area between the skull and the first cervical vertebra.

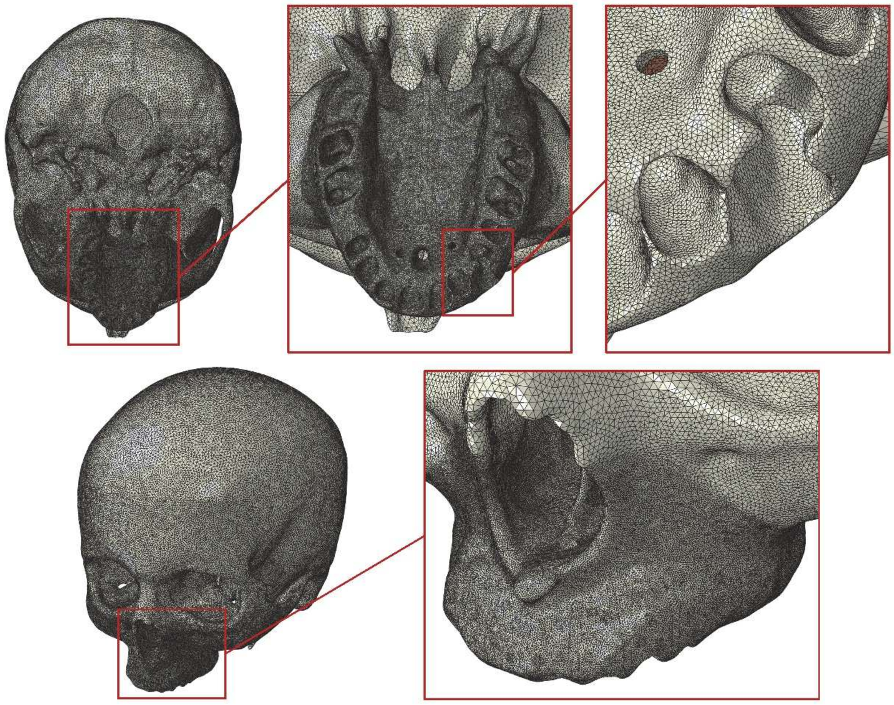


Fig. 9. Finite element mesh of skull.

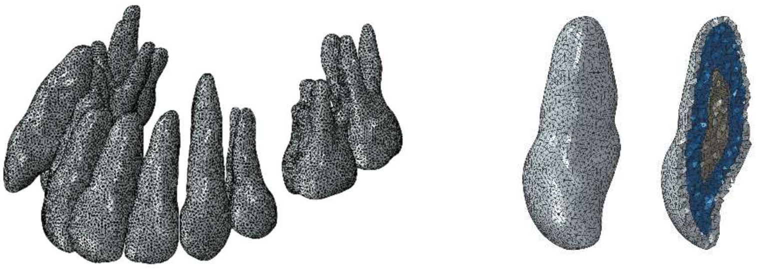
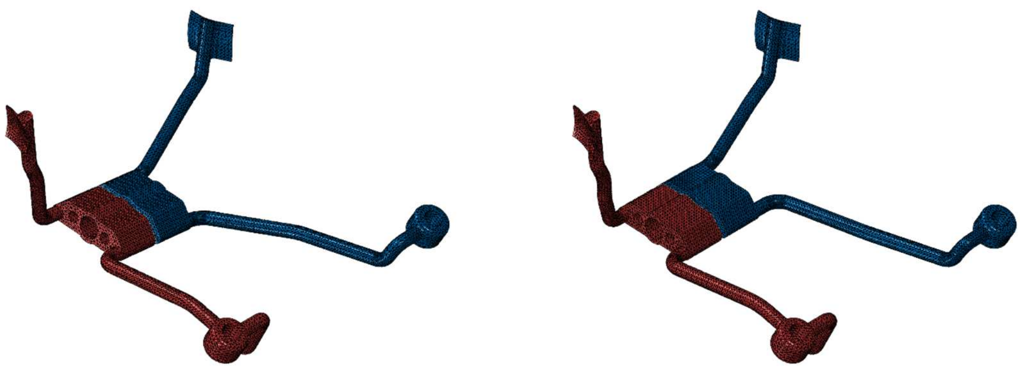


Fig. 10. Finite element mesh of teeth.

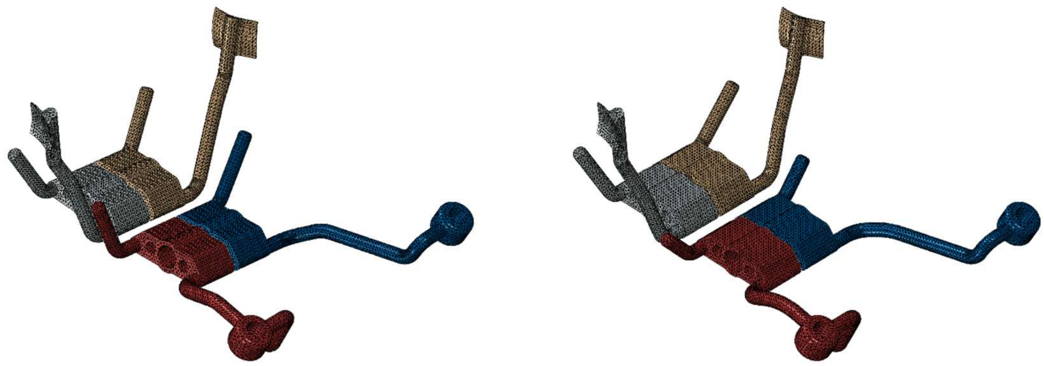
(a) (b)

Fig. 11. Finite element mesh of: (a) bands; (b) mini-screws.



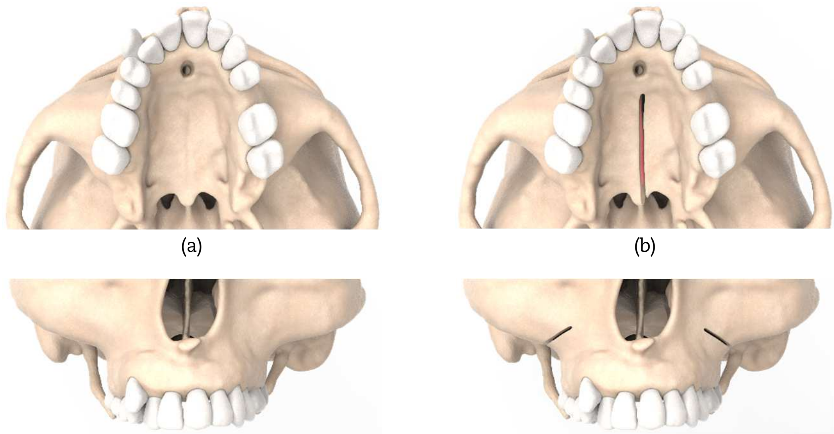
(a) (b)

Fig. 12. Finite element mesh of: (a) one-screw expander positioned parallel to the hard palate; (b) one-screw expander positioned horizontally; (c) two-screw expander positioned parallel to the palate; (d) two-screw expander positioned horizontally.



(c) (d)

Fig. 12. Continued.



(a) (b) (c) (d)

Fig. 13. (a) Before midpalatal suture osteotomy; (b) after midpalatal suture osteotomy; (c) before osteotomy of zygomatico-alveolar ridge; (d) after osteotomy of zygomatico-alveolar ridge.

Table 2. Characteristics of finite element meshes of model components.

Part			Number of Elements	Number of Nodes	Finite Element Type
Skull			5 330 264	1 032 019	Four-node Linear Solid Tetrahedral C3D4 Type
Teeth			617 803	119 335	
Acrylic Base	One-Screw Expander	Parallel to the Palate	201 372	47 276	
		Horizontal	203 452	47 652	
	Two-Screw Expander	Parallel to the Palate	218 365	51 812	
		Horizontal	216 580	51 227	
Mini-screws	Mini-screw 1		4 625	1 104	
	Mini-screw 2		4 765	1 127	
	Mini-screw 3		4 677	1 123	
	Mini-screw 4		4 834	1 147	
One-Screw Expander	Parallel to the Palate	Component 1	31 731	51 565	Ten-node Quadratic Solid Tetrahedral C3D10 Type
		Component 2	33 505	54 211	
	Horizontal	Component 1	34 956	56 537	
		Component 2	34 243	55 300	
Two-Screw Expander	Parallel to the Palate	Component 1	26 277	42 384	
		Component 2	28 139	45 068	
		Component 3	23 984	38 747	
		Component 4	24 177	39 073	
	Horizontal	Component 1	28 060	44 927	
		Component 2	25 215	40 515	
		Component 3	23 980	38 736	
		Component 4	23 643	38 273	
Bands			2 443	1 376	Three-node Linear Shell Triangular S3 Type
Total:	One-Screw Expander	Parallel to the Palate	6 236 019	1 310 283	
		Horizontal	6 242 062	1 316 720	
	Two-Screw Expander	Parallel to the Palate	6 290 353	1 374 315	
		Horizontal	6 286 889	1 370 909	

Table 3. Designations for all cases considered in the study.

	One-Screw Expander		Two-Screw Expander	
	Parallel to the palate	Horizontal	Parallel to the palate	Horizontal
Without Osteotomy	S1P1	S1H1	S2P1	S2H1
Midpalatal Suture Osteotomy	S1P2	S1H2	S2P2	S2H2
Osteotomy of Zygomatico-alveolar Ridge on the Both Sides of Maxilla	S1P3	S1H3	S2P3	S2H3
Midpalatal Suture Osteotomy with Osteotomy of Zygomatico-alveolar Ridge on the Both Sides of Maxilla	S1P4	S1H4	S2P4	S2H4

In our study, mesh sensitivity analysis was not explicitly performed. The mesh size was chosen based on the experience of previous studies [27, 29, 31]. The chosen size is small enough to provide satisfactory results consistent with those observed in the postoperative period. Meanwhile a mesh with this characteristic size allows numerical results to be obtained in a reasonable time.

2.8. Scope of the Study

Four scenarios of surgical intervention are considered within the framework of this study: without osteotomy, midpalatal suture osteotomy, osteotomy of zygomatico-alveolar ridge on the both sides of maxilla, midpalatal suture osteotomy with osteotomy of zygomatico-alveolar ridge on the both sides of maxilla (Fig. 13).

As for orthodontic appliances, two different expanders (with one expansion screw and with two expansion screws) and two positioning configurations were considered (parallel to the hard palate and horizontal) (Fig. 14).

All the above-mentioned types of surgical intervention and expander configurations are proposed by maxillofacial surgeons of FSBEI HE I.P. Pavlov SPbSMU MOH Russia and an orthodontist from North-Western State Medical University named after I.I. Mechnikov.

The considered osteotomy of zygomatico-alveolar ridge is a modified osteotomy along the line of the lower type of Le Fort. The difference is that cuts are made without reaching the piriform aperture and the pterygoid plates in the new technique, making it less invasive.

The expander model used is a novel configuration of a hybrid-type expander. Just like a standard hybrid expander, this one is attached to the first molars and supported by mini-screws in the anterior palate, as it is the optimal location for attaching the mini-screws due to the sufficient quality of bone tissue and thin mucous membrane in this region [58, 59]. The novelty of the considered expander configuration is an additional support, namely, on the distal pair of mini-screws in the region of the pterygomaxillary suture.

Let us introduce the designations for each of the cases considered in the study: Sxyz, where "S" is "screw", "x" is the number of expansion screws, "y" is the designation for the expander position, and "z" is the number of the surgical scenario. The designations for each of the cases considered are presented in Table 3.

2.9. Computational Procedure

All analyses in this paper were performed in the SIMULIA Abaqus 2021 software suite using nodes of a computing cluster based on Intel Xeon Silver 4210R CPU's and 128 GB RAM controlled by the CML-Bench® SPDM system.

The solver settings used were as follows:

- solver type – dynamic, implicit;
- nlgeom – on;
- applications – quasi-static;
- incrementation – automatic;
- maximum number of increments – 100;
- initial increment size – 0.01;
- minimum increment size – 1E-05;
- maximum increment size – software default.

Since there were no convergence issues during the solution process, the default Abaqus convergence criteria were left unchanged.

Computations for each case take about three hours.

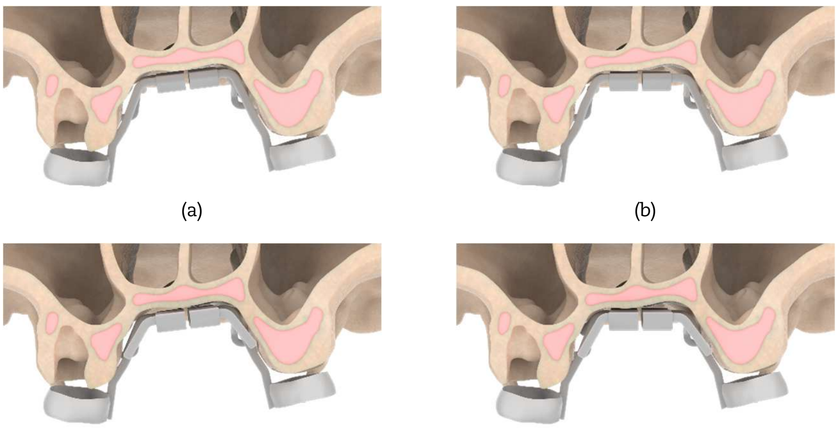


Fig. 14. (a) One-screw expander positioned parallel to the hard palate; (b) one-screw expander positioned horizontally; (c) two-screw expander positioned parallel to the hard palate; (d) two-screw expander positioned horizontally.

2.10. Model Validation and Verification

We do not perform validation and verification in our study because the types of surgical intervention and expander configurations considered are experimental, i.e., the corresponding experimental data are currently unavailable. On the other hand, the results of our computations can help determine whether it is reasonable to conduct human subject research.

Drawing on the existing knowledge and experience, we strive to ensure validity of the current results based on our earlier findings, consistent with those observed in the postoperative period [27, 29, 31]. Our working group included doctors as an additional guarantee of validity.

3. Results

3.1. Displacements in the Maxilla

The distribution of displacements of teeth and bone structures of the palate in the transverse direction for all considered cases is shown in Fig. 15. For clarity, the same legend was used for all cases.

Osteotomy of zygomatico-alveolar ridge induces additional displacements of bone structures of the alveolar ridge near the anchor teeth and the posterior maxilla. Furthermore, this extent of surgical intervention contributes to a more symmetrical distribution of displacements. As a result of midpalatal suture osteotomy, displacements are observed in the entire posterior maxilla. On the other hand, performing midpalatal suture osteotomy with osteotomy of zygomatico-alveolar ridge leads to a slightly more symmetrical displacement distribution compared to only midpalatal suture osteotomy.

If a two-screw expander is used in any of the surgical scenarios, the displacements cover wider areas, especially the posterior maxilla. The horizontally positioned expander contributes to a more symmetrical expansion of the maxilla. If the expander is positioned parallel to the palate, larger displacements are observed on the lower side of the maxilla.

The expansion was measured at three locations of the midpalatal suture (A, B, and C) to assess its shape after expansion in each case. However, since the finite element model used does not include the midpalatal suture, control points were introduced to assess its expansion. Three pairs of nodes – A, B, and C – were selected on the sides of the boundary of the midpalatal osteotomy region (Fig. 16). Thus, the relative displacement of each pair of nodes determines the value of the expansion of midpalatal suture at the corresponding location.

The expansion values at different points of the maxilla and their percentages to the total expansion of the screw for all considered cases are given in Table 4. The variations in the expansion value along the midpalatal suture from point A to point C are shown in Fig. 17.

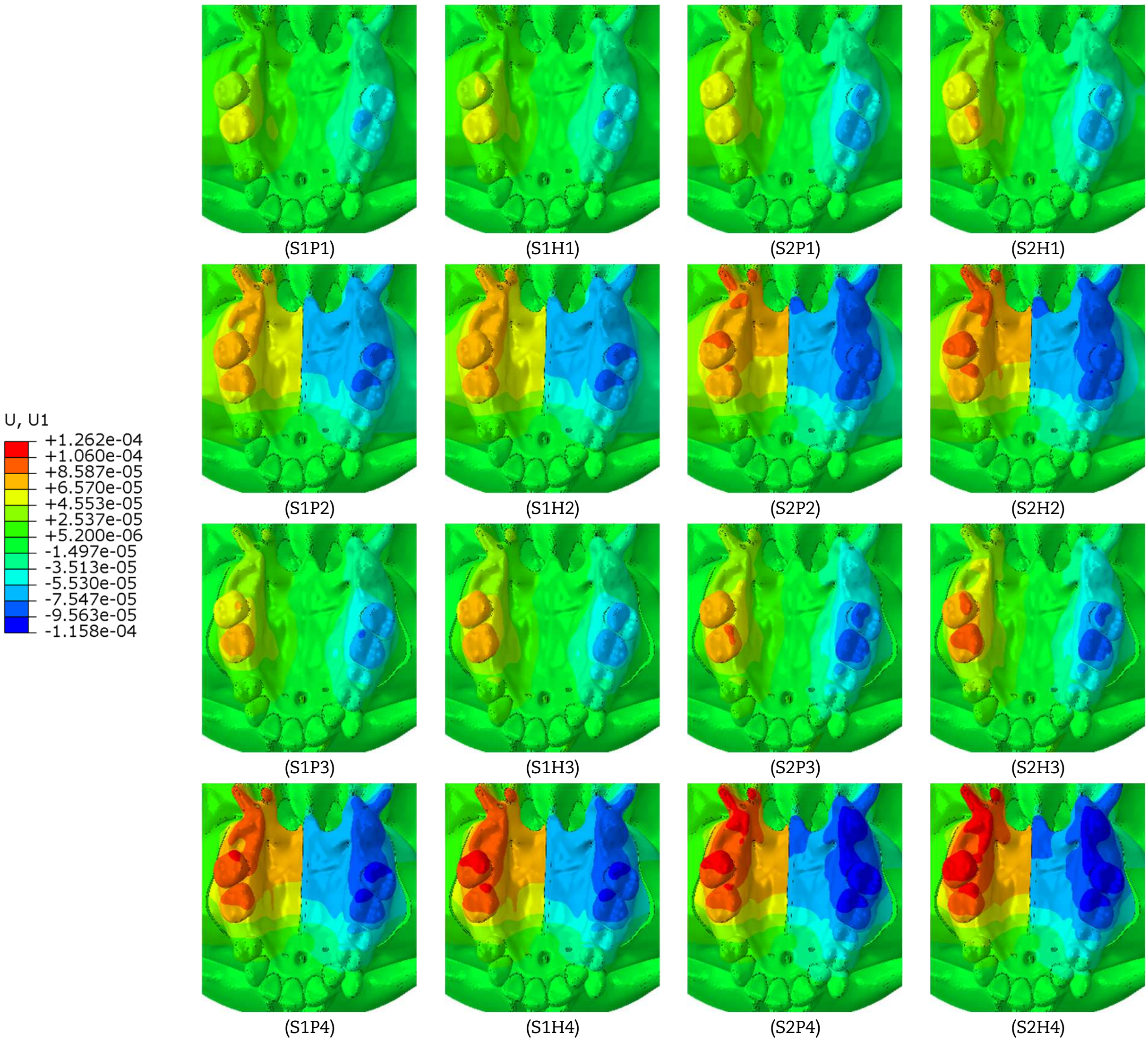


Fig. 15. Distribution of transverse displacements in the maxilla (m).

Table 4. Expansion values at different points of the maxilla and their percentages to the total expansion of the screw.

	Expansion Value (μm)					% of the Total Screw Expansion			
	Point A	Point B	Point C	First Molars		Point A	Point B	Point C	First Molars
S1P1	0.5	2.4	2.2	119.2	S1P1	0.2	1.0	0.9	47.7
S1P2	119.5	114.8	55.5	169.6	S1P2	47.8	45.9	22.2	67.8
S1P3	0.5	2.5	2.4	156.3	S1P3	0.2	1.0	1.0	62.5
S1P4	138.9	128.0	58.8	212.7	S1P4	55.6	51.2	23.5	85.1
S1H1	0.5	2.4	2.4	120.6	S1H1	0.2	1.0	1.0	48.2
S1H2	120.7	115.9	56.0	173.7	S1H2	48.3	46.4	22.4	69.5
S1H3	0.5	2.5	2.5	159.6	S1H3	0.2	1.0	1.0	63.8
S1H4	139.8	128.8	59.2	218.6	S1H4	55.9	51.5	23.7	87.4
S2P1	0.9	3.4	2.2	137.6	S2P1	0.4	1.4	0.9	55.0
S2P2	145.1	131.7	58.2	187.6	S2P2	58.0	52.7	23.3	75.0
S2P3	0.9	3.5	2.3	181.7	S2P3	0.4	1.4	0.9	72.7
S2P4	161.7	142.8	60.6	234.7	S2P4	64.7	57.1	24.2	93.9
S2H1	0.9	3.6	2.4	143.7	S2H1	0.4	1.4	1.0	57.5
S2H2	148.3	135.2	59.2	193.2	S2H2	59.3	54.1	23.7	77.3
S2H3	0.9	3.7	2.5	190.8	S2H3	0.4	1.5	1.0	76.3
S2H4	164.3	145.1	61.4	241.2	S2H4	65.7	58.0	24.6	96.5

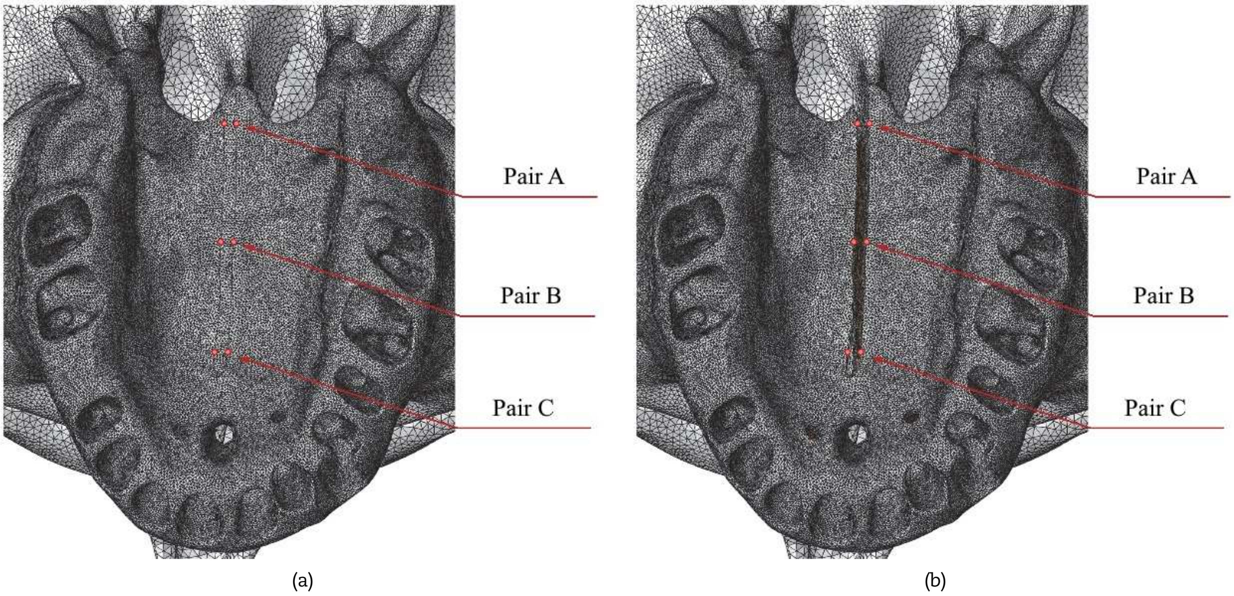


Fig. 16. Positions of the pairs of control points for measuring expansion of midpalatal suture: (a) without midpalatal suture osteotomy; (b) with midpalatal suture osteotomy.

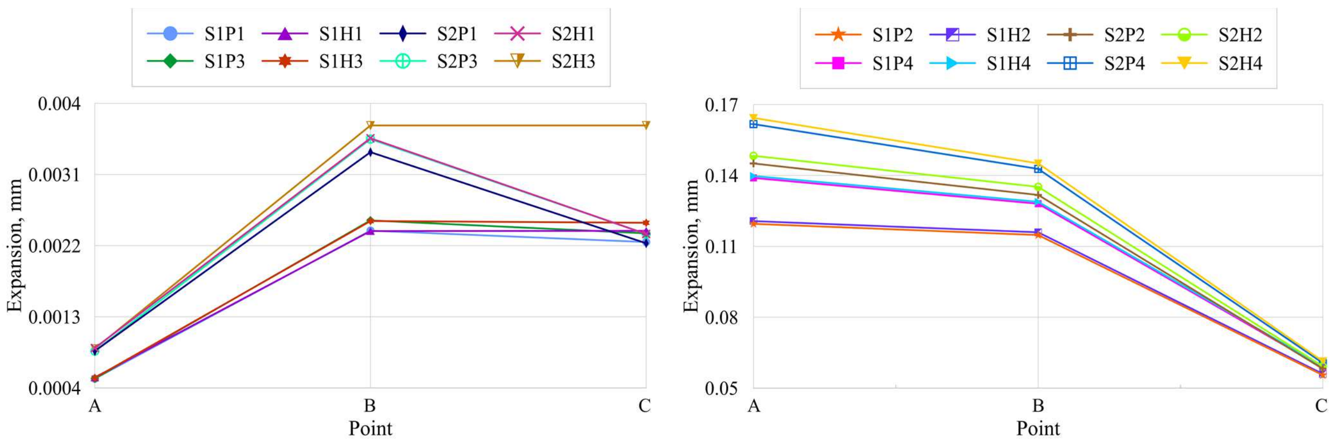


Fig. 17. Variation in expansion along the midpalatal suture from point A to point C: (a) for the cases without midpalatal suture osteotomy; (b) for the cases with midpalatal suture osteotomy.

A greater expansion is observed in all cases considered at the dental level than at the skeletal level, which is a logical and predictable result.

The expansion of the midpalatal suture is small in the cases without surgical intervention (0.9–1.4% of the total expansion of the screw), and the increase in the transverse dimensions of the maxilla occurs due to the teeth spreading apart and tipping. In this case, minimum expansion is observed in the posterior midpalatal suture and maximum expansion is observed in the middle part of the midpalatal suture. Mean values of expansion are observed in the anterior midpalatal suture. Thus, the shape of the midpalatal suture expansion is a pentagon with its base in the anterior palate. Osteotomy of zygomatico-alveolar ridge on the both sides of maxilla has practically no effect on the size and the shape of the midpalatal suture expansion but produces a greater expansion at the dental level by 31.1–32.8%. A significantly greater expansion of the midpalatal suture is observed as a result of midpalatal suture osteotomy, taking the shape of a triangle with a base in the posterior palate. In addition, midpalatal suture osteotomy leads to an 8.5–8.8% greater expansion at the dental level compared to osteotomy of zygomatico-alveolar ridge in the cases when the one-screw expander is used. Finally, midpalatal suture osteotomy combined with osteotomy of zygomatico-alveolar ridge leads to maximum expansion of the midpalatal suture (55.6–65.7% of the total expansion of the screw) and maximum expansion of the maxilla at the dental level (85.1–96.5% of the total expansion of the screw).

Using the two-screw expander leads to a 21.4–22.9% greater expansion of the midpalatal suture in the cases with midpalatal suture osteotomy, but does not affect its shape. Using the two-screw expander does not affect either the expansion value or the shape of the midpalatal suture expansion in the other half of the cases. Moreover, using the two-screw expander leads to a 10.3–19.5% greater expansion at the dental level compared to the one-screw expander in all cases.

Changing the position of the expander does not affect the shape of the midpalatal suture expansion and the expansion value at the dental level. However, positioning the expander horizontally in the cases when midpalatal suture osteotomy is performed provides a 0.6–2.2% greater expansion compared to the expander positioned parallel to the palate. In other cases, changing the position of the expander does not affect the expansion value of the midpalatal suture.

3.2. Stresses and Plastic Strains in the Cortical Layer of the Bones of the Hard Palate

The distributions of stresses and plastic strains in the cortical layer of the hard palate for all considered cases are shown in Figs. 18–21 and Figs. 22–27, respectively. The maximum values of the plastic strains are given in Table 5.

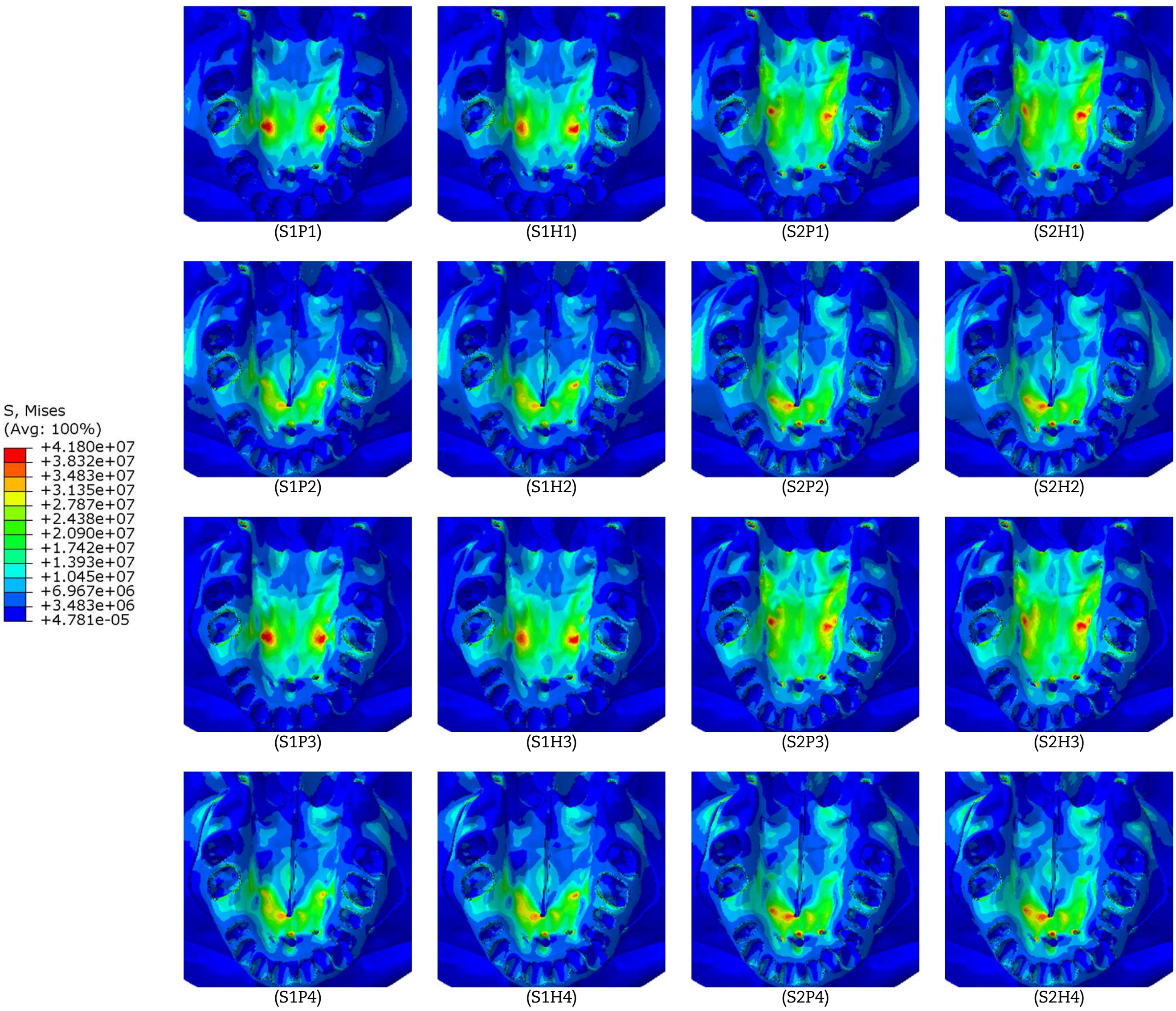


Fig. 18. Von Mises stress in the cortical layer of the hard palate (Pa).

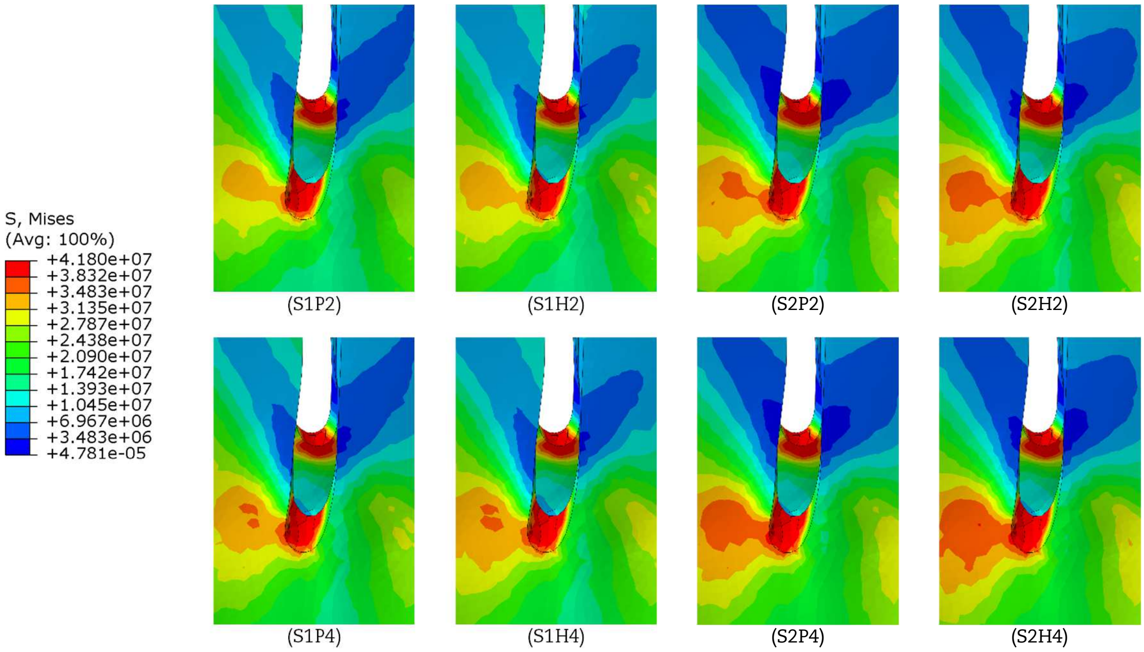


Fig. 19. Von Mises stress in the cortical layer of the hard palate in midpalatal osteotomy region (Pa).

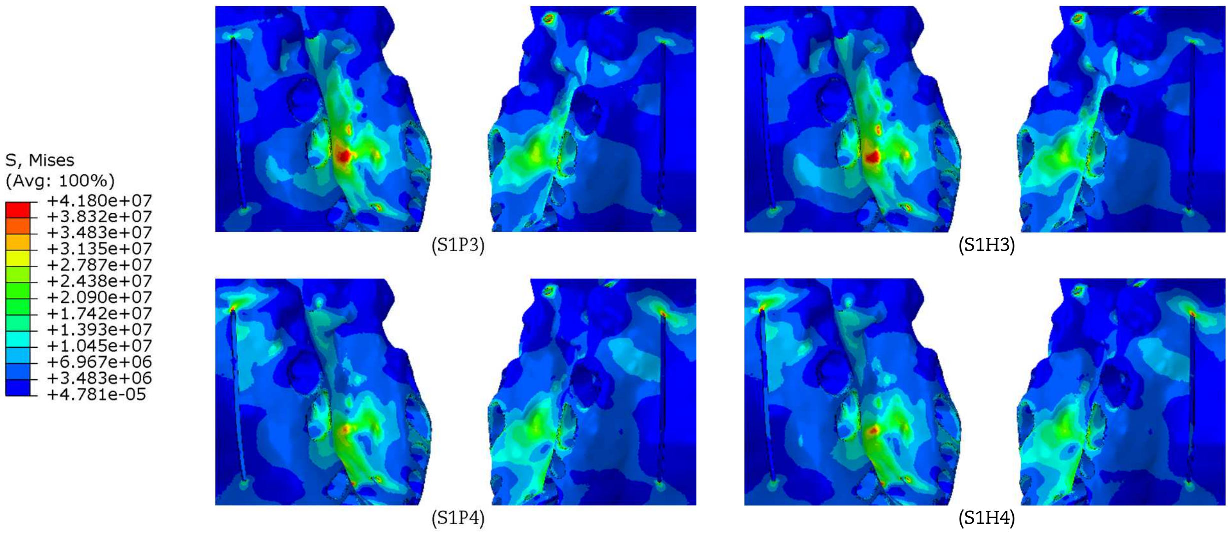


Fig. 20. Von Mises stress in the cortical layer of the hard palate in the region of the osteotomy of zygomatico-alveolar ridge for the cases with one-screw expander (Pa).

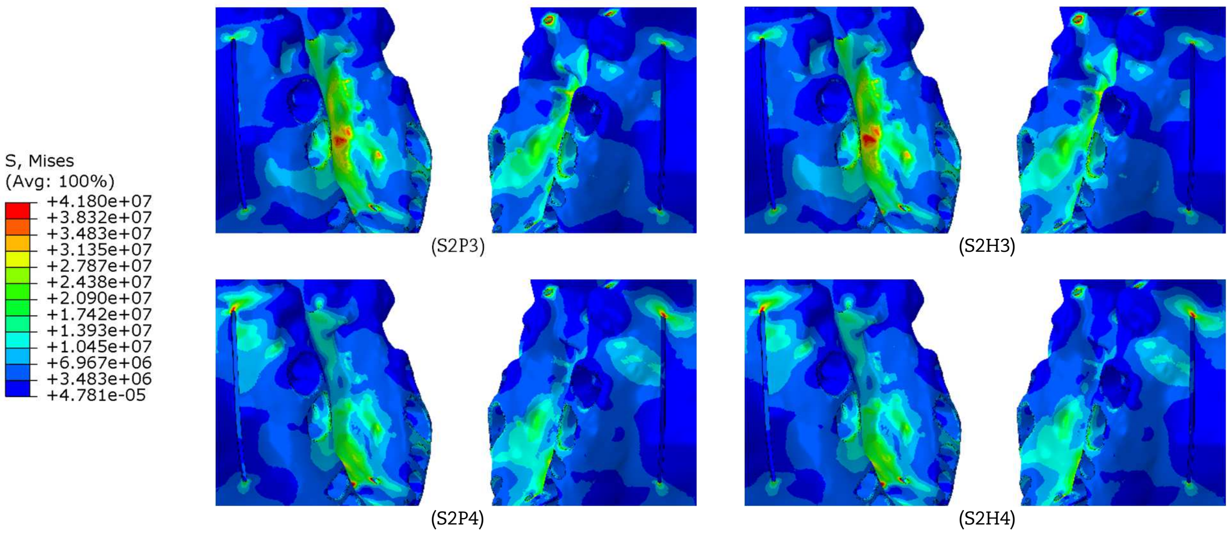


Fig. 21. Von Mises stress in the cortical layer of the hard palate in the region of the osteotomy of zygomatico-alveolar ridge for the cases with two-screw expander (Pa).

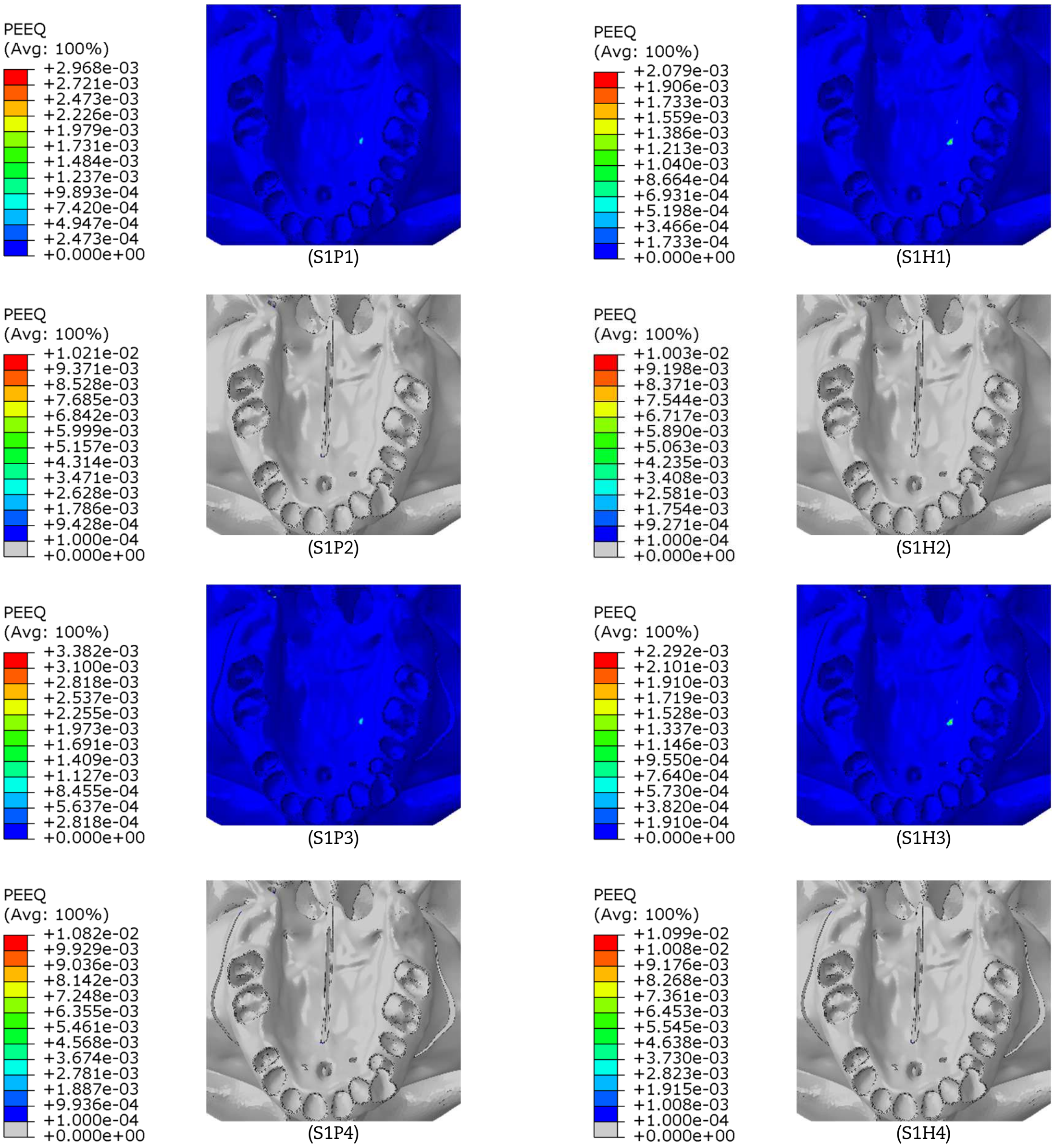


Fig. 22. Distribution of plastic strains in the cortical layer of the hard palate for the cases with one-screw expander.

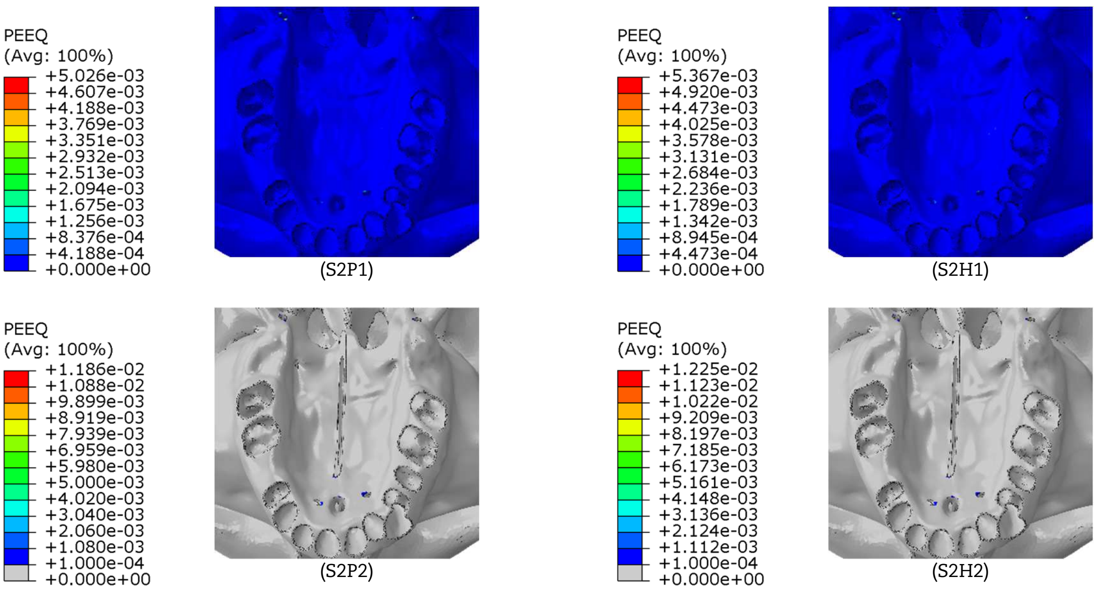


Fig. 23. Distribution of plastic strains in the cortical layer of the hard palate for the cases with two-screw expander.

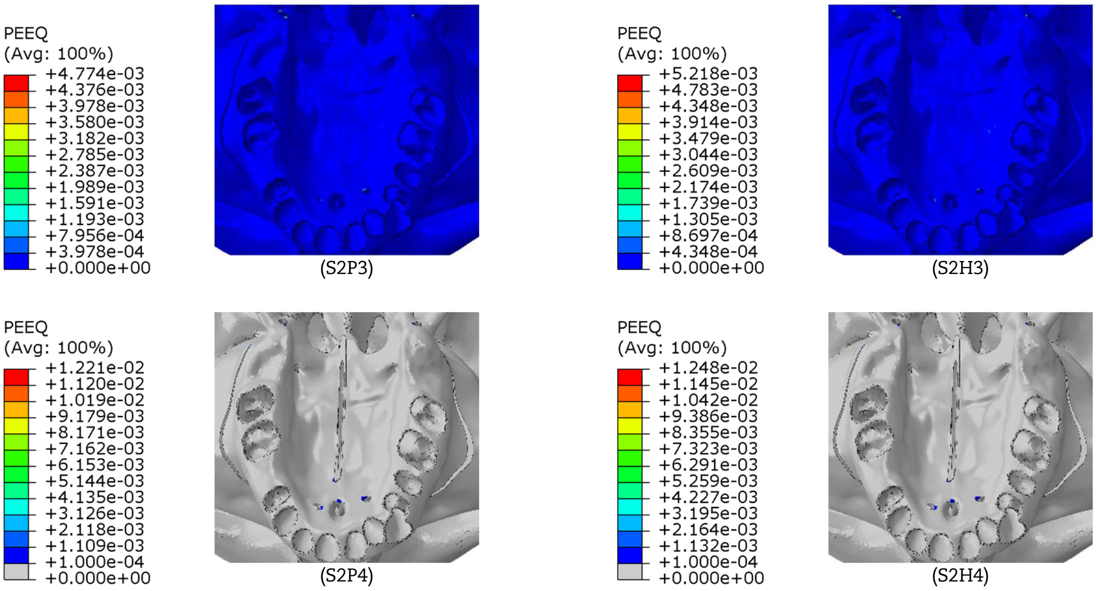


Fig. 23. Continued.

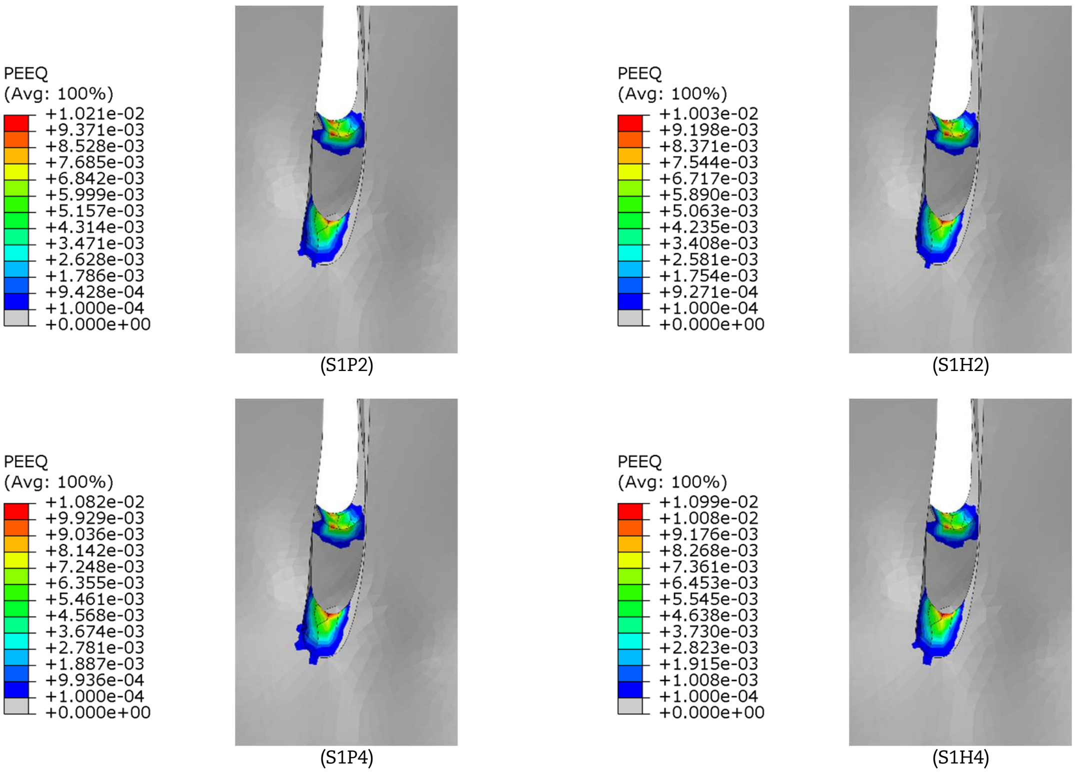


Fig. 24. Distribution of plastic strains in the cortical layer of the hard palate in midpalatal osteotomy region for the cases with one-screw expander.

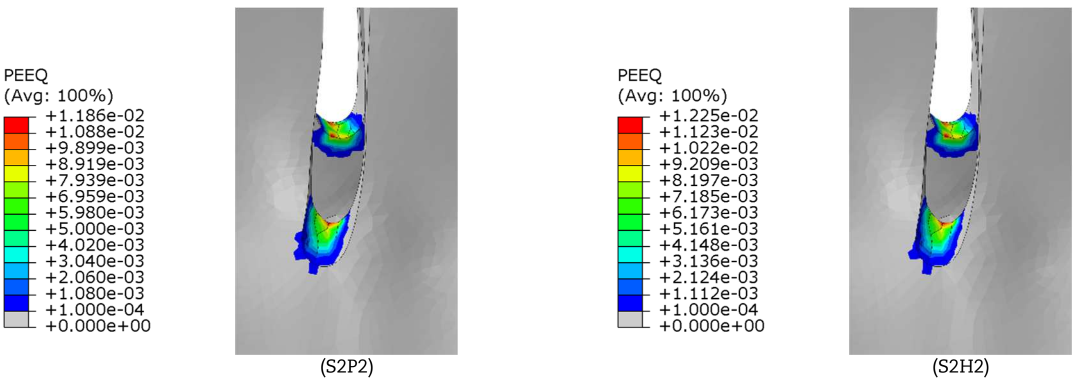


Fig. 25. Distribution of plastic strains in the cortical layer of the hard palate in midpalatal osteotomy region for the cases with two-screw expander.

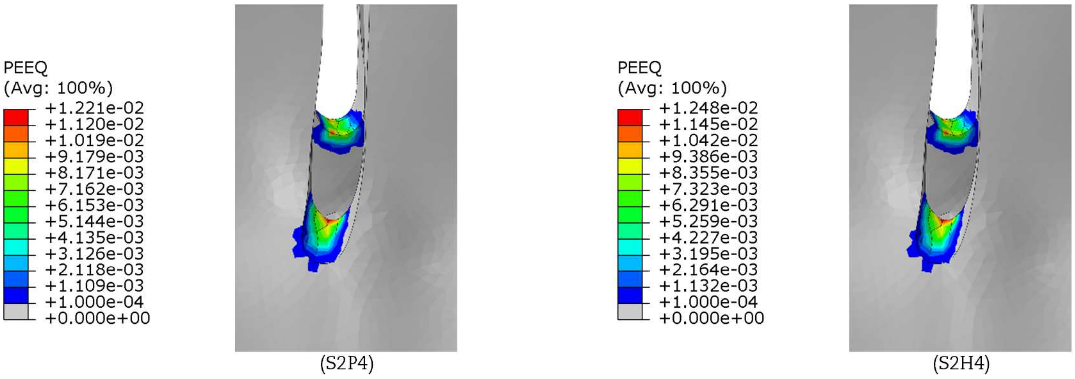


Fig. 25. Continued.

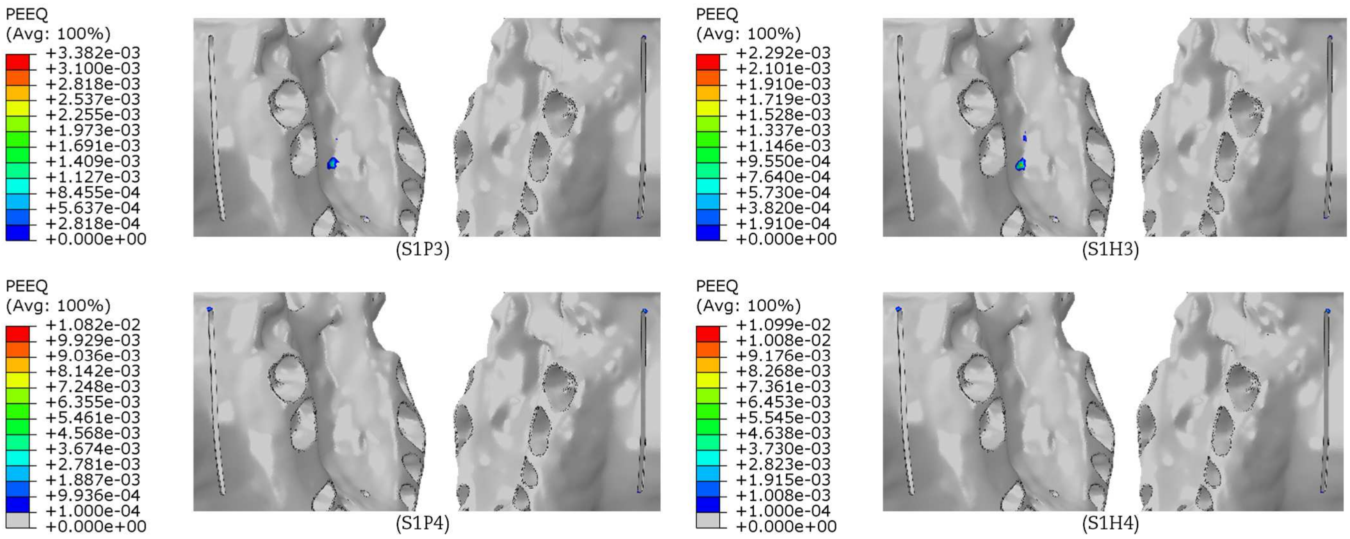


Fig. 26. Distribution of plastic strains in the cortical layer of the hard palate in the region of the osteotomy of zygomatico-alveolar ridge for the cases with one-screw expander.

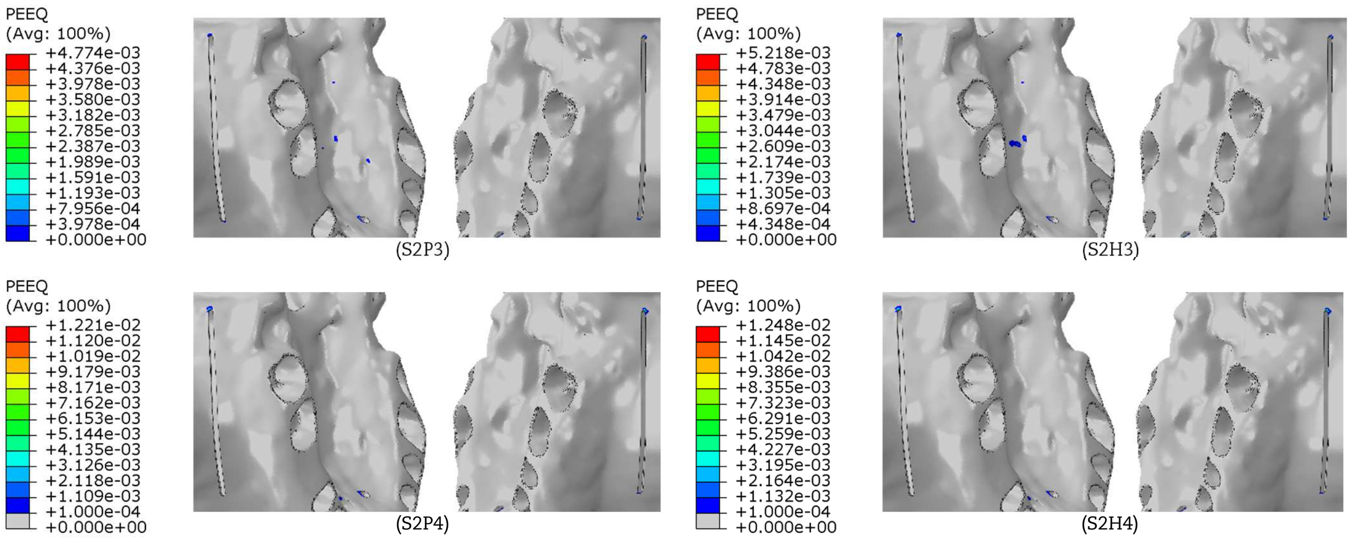


Fig. 27. Distribution of plastic strains in the cortical layer of the hard palate in the region of the osteotomy of zygomatico-alveolar ridge for the cases with two-screw expander.

Table 5. Maximum plastic strains in the cortical layer of the hard palate.

	Equivalent Plastic Strain in the Cortical Bone (%)		Equivalent Plastic Strain in the Cortical Bone (%)		Equivalent Plastic Strain in the Cortical Bone (%)		Equivalent Plastic Strain in the Cortical Bone (%)
S1P1	0.297	S1H1	0.208	S2P1	0.503	S2H1	0.537
S1P2	1.021	S1H2	1.003	S2P2	1.186	S2H2	1.225
S1P3	0.338	S1H3	0.229	S2P3	0.477	S2H3	0.522
S1P4	1.082	S1H4	1.099	S2P4	1.221	S2H4	1.248

Table 6. Maximum values of plastic strains in the cancellous layer of the bones of the hard palate.

	Equivalent Plastic Strain in the Cancellous Bone (%)		Equivalent Plastic Strain in the Cancellous Bone (%)		Equivalent Plastic Strain in the Cancellous Bone (%)		Equivalent Plastic Strain in the Cancellous Bone (%)
S1P1	0.286	S1H1	0.143	S2P1	0.303	S2H1	0.307
S1P2	2.020	S1H2	1.990	S2P2	2.198	S2H2	2.218
S1P3	0.280	S1H3	0.141	S2P3	0.301	S2H3	0.296
S1P4	2.017	S1H4	2.009	S2P4	2.122	S2H4	2.193

Highly stressed regions are observed near the holes where the mini-screws are installed, near the osteotomy sites, and in the contact regions between the acrylic base and the hard palate in all cases considered.

Regardless of the expander configuration used and its position, the stresses in the cases without surgical intervention are localized mainly in the medial and anterior regions of the hard palate, as well as in the alveoli of the anchor teeth.

A slightly wider stress distribution is observed in the cases with osteotomy of zygomatico-alveolar ridge. Besides, this extent of surgical intervention does not affect the existing highly stressed regions in any way. We can also note that the osteotomy of zygomatico-alveolar ridge in combination with using the one-screw expander leads to a 10.1–13.8% increase in plastic strain, while using the two-screw expander leads to a 0.3–7.9% decrease in plastic strain.

As a result of performing the midpalatal suture osteotomy, the stresses are localized predominantly in the anterior palate, and a decrease in the size of highly stressed regions is observed near the holes for mini-screws and the contact region between the acrylic base and the hard palate. At the same time, an additional highly stressed region appears near the incisive foramen. It is also worth noting that plastic strains decrease by 44.6–81.8% near the holes in the posterior maxilla and in the contact region between the acrylic base and the palate as a result of this surgical technique, but much greater (by 2.3–4.8 times) plastic strains appear near the osteotomy sites.

Midpalatal suture osteotomy with osteotomy of zygomatico-alveolar ridge on the both sides of maxilla results in a slightly wider stress distribution than only midpalatal suture osteotomy. Moreover, this extent of surgical intervention increases the highly stressed regions near the osteotomy sites and near the incisive foramen. It also leads to a 1.9–9.6% increase in plastic strain near the osteotomy sites and an increase in the size of the regions of plastic strain near the incisive foramen and the holes for installing the mini-screws in the anterior maxilla.

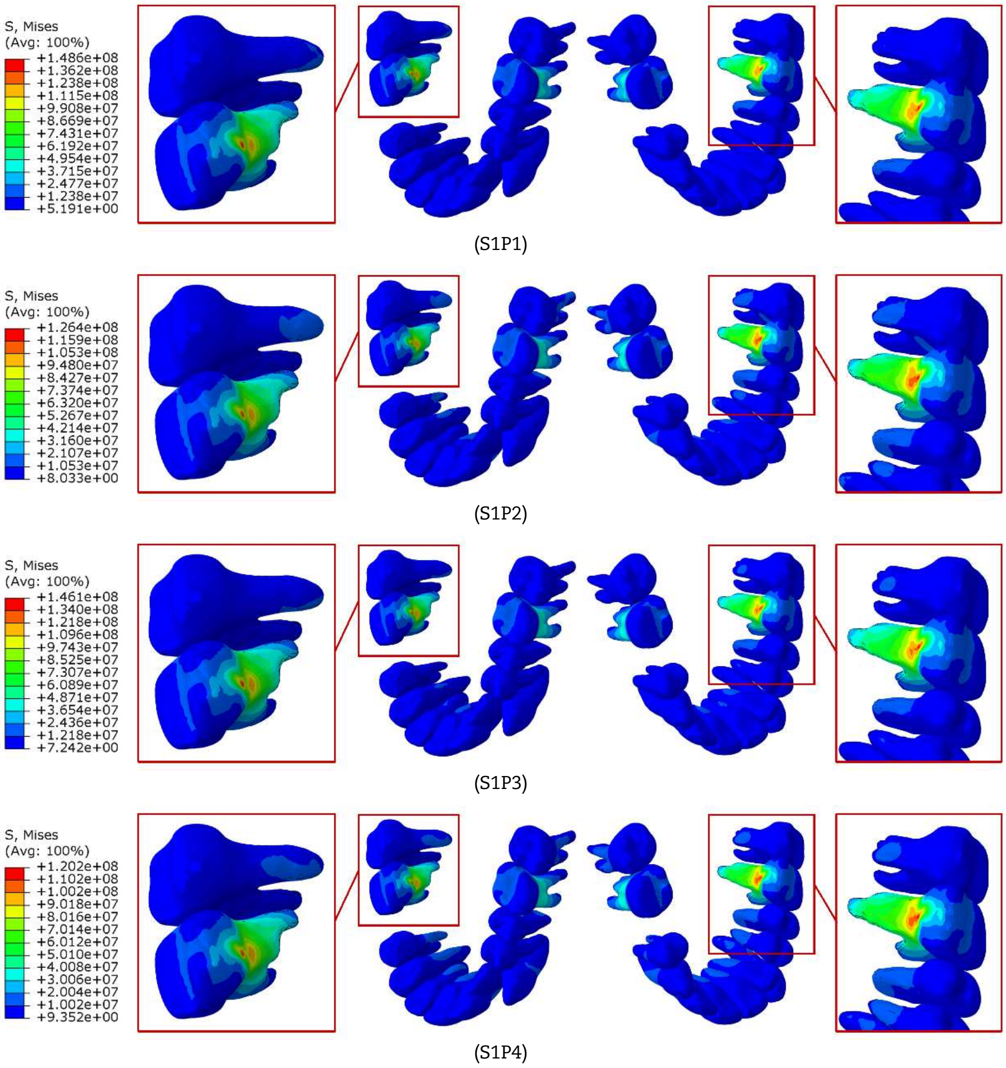
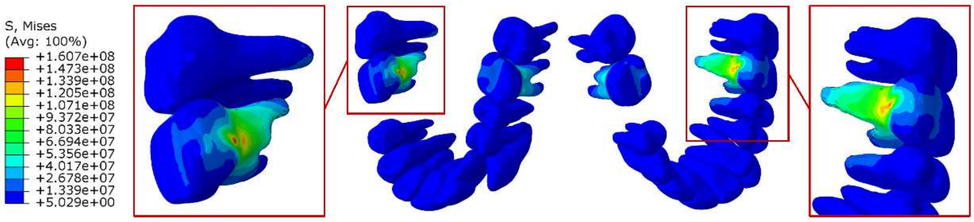
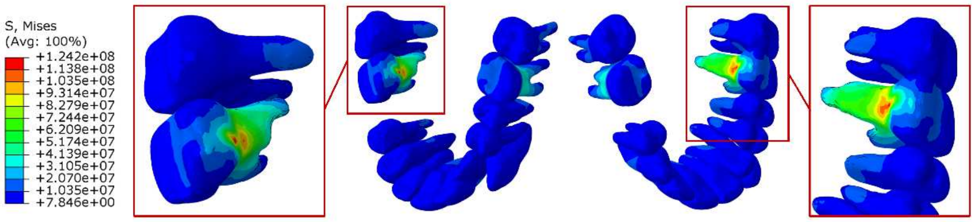


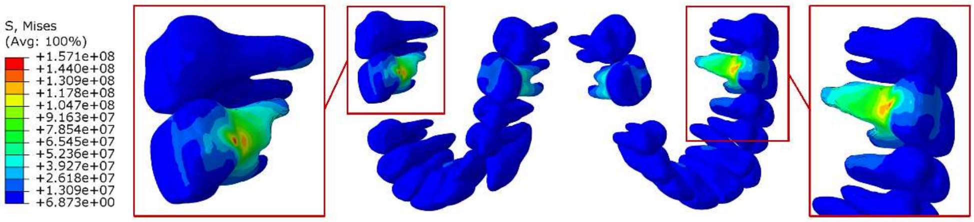
Fig. 28. Von Mises stress in the teeth for the cases with one-screw expander positioned parallel to the hard palate (Pa).



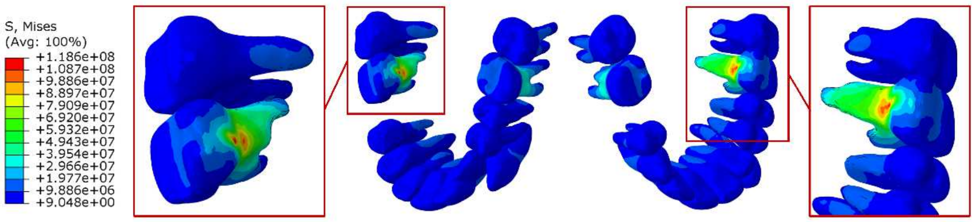
(S1H1)



(S1H2)

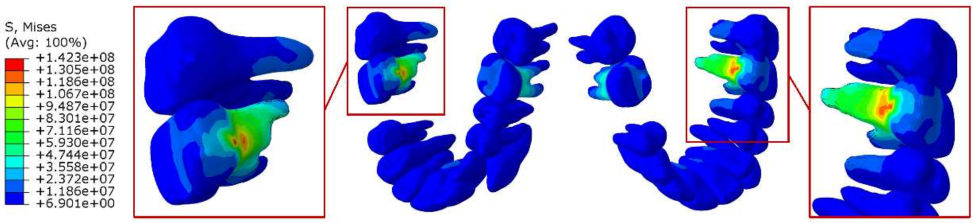


(S1H3)

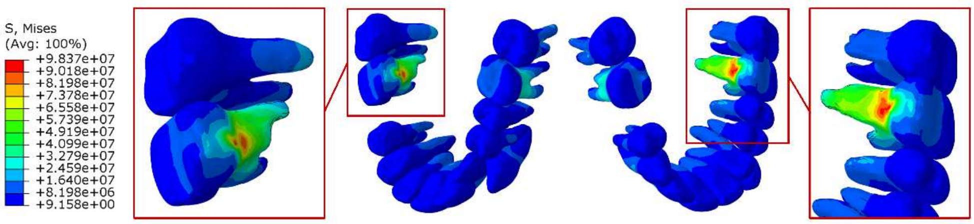


(S1H4)

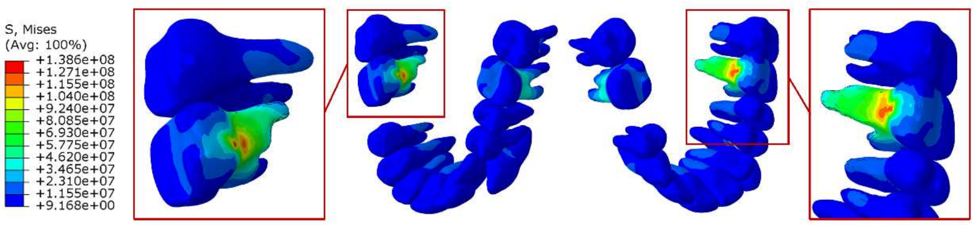
Fig. 29. Von Mises stress in the teeth with one-screw expander positioned horizontally (Pa).



(S2P1)

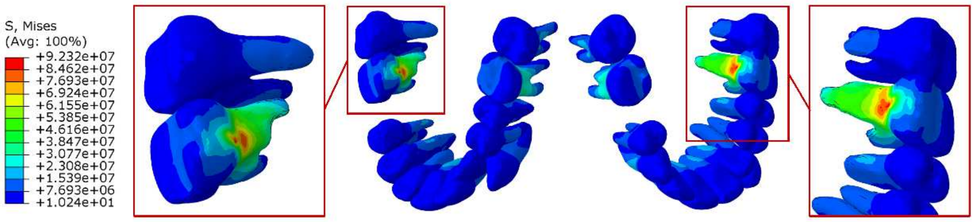


(S2P2)



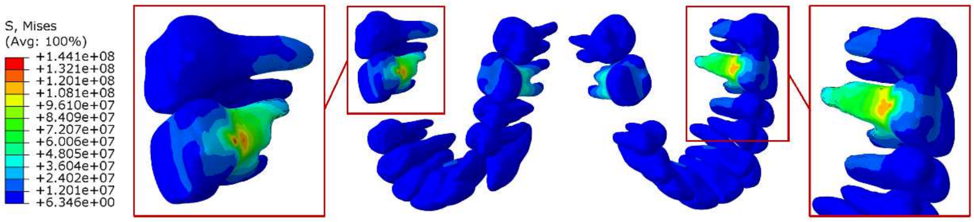
(S2P3)

Fig. 30. Von Mises stress in the teeth with two-screw expander positioned parallel to the hard palate (Pa).

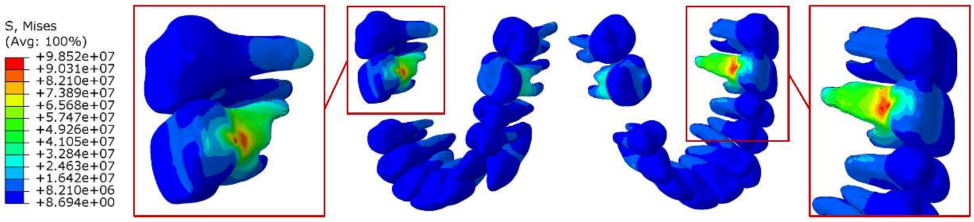


(S2P4)

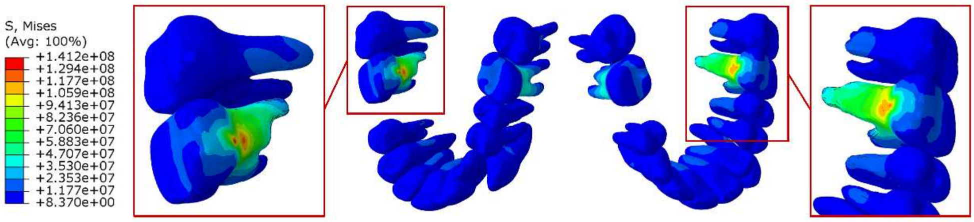
Fig. 30. Continued.



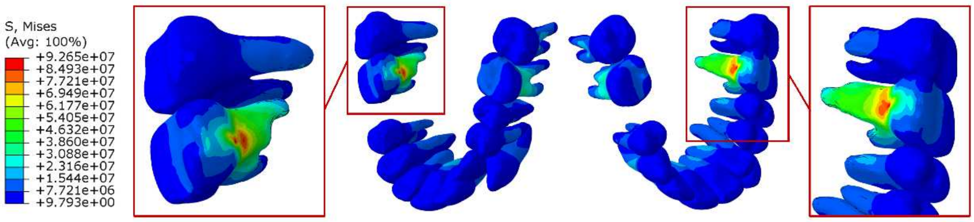
(S2H1)



(S2H2)



(S2H3)



(S2H4)

Fig. 31. Von Mises stress in the teeth with two-screw expander positioned horizontally (Pa).

Using the two-screw expander in any of the surgical scenarios produces a wider stress distribution along the palate, additionally causing an increase in the size of highly stressed regions and a 12.9–128.0% increase in plastic strains near the holes and the osteotomy sites.

Changing the position of the expander practically does not affect the stress distribution, and also does not have a consistent effect on the magnitude of plastic strains.

3.3. Stresses and Plastic Strains in the Cancellous Layer of the Bones of the Hard Palate

The distribution of stresses and plastic strains is similar in the cortical and cancellous layers of the palatine bone. The maximum values of plastic strains in the cancellous layer for all considered cases are given in Table 6.

Table 7. Maximum stresses in the teeth.

	Von Mises Stress in Teeth (MPa)		Von Mises Stress in Teeth (MPa)		Von Mises Stress in Teeth (MPa)		Von Mises Stress in Teeth (MPa)
S1P1	160.7	S1H1	148.6	S2P1	144.1	S2H1	142.3
S1P2	124.2	S1H2	126.4	S2P2	98.5	S2H2	98.4
S1P3	157.1	S1H3	146.1	S2P3	141.2	S2H3	138.6
S1P4	118.6	S1H4	120.2	S2P4	92.7	S2H4	92.3

Table 8. Maximum plastic strains in one-screw expander retentions.

	Equivalent Plastic Strain in One-Screw Expander (%)		Equivalent Plastic Strain in One-Screw Expander (%)
S1P1	4.797	S1H1	8.693
S1P2	3.364	S1H2	6.235
S1P3	4.616	S1H3	8.330
S1P4	3.121	S1H4	5.774

Table 9. Maximum plastic strains in two-screw expander retentions.

	Equivalent Plastic Strain in Two-Screw Expander (%)			Equivalent Plastic Strain in Two-Screw Expander (%)	
	Front Screw	Back Screw		Front Screw	Back Screw
S2P1	6.431	0.308	S2H1	5.468	0.311
S2P2	4.072	0.040	S2H2	3.066	0.048
S2P3	6.225	0.248	S2H3	5.226	0.252
S2P4	3.792	0.000	S2H4	2.766	0.000

Table 10. Maximum stresses in anchoring bands.

	Von Mises Stress in Bands (MPa)		Von Mises Stress in Bands (MPa)		Von Mises Stress in Bands (MPa)		Von Mises Stress in Bands (MPa)
S1P1	314.4	S1H1	302.3	S2P1	238.1	S2H1	286.8
S1P2	226.1	S1H2	233.2	S2P2	167.1	S2H2	158.5
S1P3	304.5	S1H3	293.6	S2P3	233.8	S2H3	280.1
S1P4	213.4	S1H4	220.6	S2P4	158.3	S2H4	147.8

Table 11. Maximum stresses in the mini-screws.

	Von Mises Stress in Mini-Screws (MPa)			Von Mises Stress in Mini-Screws (MPa)			Von Mises Stress in Mini-Screws (MPa)			Von Mises Stress in Mini-Screws (MPa)	
	Front Mini-Screws	Back Mini-Screws		Front Mini-Screws	Back Mini-Screws		Front Mini-Screws	Back Mini-Screws		Front Mini-Screws	Back Mini-Screws
S1P1	127.6	279.0	S1H1	140.1	244.2	S2P1	171.1	303.9	S2H1	161.5	316.2
S1P2	82.4	200.3	S1H2	90.5	178.6	S2P2	131.2	196.0	S2H2	127.0	199.6
S1P3	124.5	284.7	S1H3	136.0	250.3	S2P3	166.8	308.1	S2H3	157.1	320.9
S1P4	79.4	189.7	S1H4	84.8	170.1	S2P4	128.4	185.1	S2H4	123.5	189.6

Osteotomy of zygomatico-alveolar ridge leads to a slight decrease in plastic strains (by 0.7–3.6%). Midpalatal suture osteotomy leads to 7.1–13.9 times larger plastic strains. Midpalatal suture osteotomy with osteotomy of zygomatico-alveolar ridge does not have a consistent effect on the magnitude of plastic strains compared to only the midpalatal suture osteotomy.

Using the two-screw expander leads to a 5.2–114.7% increase in plastic strains. Changing the position of the expander does not have a consistent effect on the magnitude of plastic strains.

3.4. Stresses in the Teeth

The stress distributions in the teeth for all the cases considered is shown in Figs. 28–31. The maximum values of these stresses are given in Table 7.

The stresses are primarily localized in the anchor teeth in all cases. To be more precise, the regions with higher stresses are observed in the necks of the teeth in the region where the expander presses into them.

Regardless of the expander configuration used and its position, osteotomy of zygomatico-alveolar ridge slightly reduces stress in the teeth (by 1.7–2.6%). Midpalatal suture osteotomy provides a stress reduction by 14.9–30.9%. Midpalatal suture osteotomy with osteotomy of zygomatico-alveolar ridge leads to slightly lower (by 4.5–6.2%) stresses than only the midpalatal suture osteotomy.

Using the two-screw expander in any surgical scenario leads to lower stresses in the anchor teeth (by 4.2–23.2%). Changing the position of the expander does not have a consistent effect on the magnitude of the stresses.

3.5. Stresses and Plastic Strains in the Expanders, Bands and Mini-screws

Local plastic strains are observed in the retention arms of the expander in most cases. The maximum values of these strains for all cases considered are given in Tables 8 and 9.

The stresses were localized near the anchoring bands in the region where the expander pressed into them. The maximum values of these stresses for all cases considered are given in Table 10.

The stresses in the anterior palate mini-screws (front mini-screws) were localized in the regions located near the first cortical layer of the bone of the hard palate in all cases considered. The stresses in the posterior palate mini-screws (back mini-screws) were localized around the gaps between the anchorage to the expander retentions and the regions where the mini-screws penetrate the bone. The maximum values of these stresses for all cases considered are given in Table 11.

4. Discussion

4.1. Criteria for Determining the Optimal Technique

Rapid maxillary expansion is considered successful if the optimal width of the dental arch is reached. And it is crucial for the increase in transverse dimensions to be skeletal, not dental. This determines the stability in the treatment of the deformity, since teeth displaced by orthodontic appliances tend to return to their original position [45]. However, the conclusions in this study rely on the differences in the simulation results rather than on absolute values of the quantities to avoid systematic error. An additional criterion for the optimal result of maxillary expansion is the minimization of peak stresses near the holes for mini-screws, reducing the risk of bone resorption.

4.2. Surgical Intervention Scenario

The results of the finite element modelling carried out indicate that different distributions of stresses and displacements can be expected depending on the surgical intervention scenario. However, high stresses are observed near the holes for mini-screws, near the osteotomy sites and in the contact regions between the acrylic base and the palate in all cases considered. In addition, local plastic strains are observed in these regions in most cases. The above factors are known to increase the risk of bone resorption.

4.2.1. Without Surgical Intervention

The stresses are localized mainly in the medial and anterior regions of the hard palate as well as in the alveoli and necks of the anchor teeth in the cases without surgical intervention. Such a wide distribution of stresses indicates that the force exerted by the expander is spent on loading bone tissue and teeth. However, it is worth noting that the cause of the highly stressed regions in the teeth may be due to the linearity of the contact interaction between the teeth and their alveoli.

It is also mainly the anchor teeth that are displaced, that is, the increase in the transverse dimensions of the maxilla is primarily dental. This can negatively affect the stability of treatment results.

The maxillary expansion value at the dental level ranges from 47.7% to 57.5% of the total expansion of the screw. This is consistent with the results obtained by Yoon S., Lee D.-Y. and Jung S.-K. [49] for a bone-borne expander with the mini-screws inserted in the anterior and posterior regions. Thus, it can be assumed for the cases without surgical intervention that the maxillary expansion value provided by the modified hybrid-type expander at the dental level is the same as that provided by the expander only supported by mini-screws in the palatine bone. The maximum expansion of the midpalatal suture in this study ranges from 1.0% to 1.4% of the total expansion of the screw. The reason for the discrepancy between the real values of maxillary expansion and the total expansion of the screw is that the expansion of the screw is distributed through the maxillary structures with finite stiffness, or, in other words, with a certain compliance. The small ratio of the expansion value in the midpalatal suture to the total expansion of the screw is observed because the maxillary structures have the maximum possible stiffness in the cases without surgical intervention.

4.2.2. Osteotomy of Zygomatico-Alveolar Ridge on the Both Sides of Maxilla

The osteotomy of the zygomatico-alveolar ridge on the both sides of maxilla has no effect on the existing highly stressed regions in the hard palate and slightly reduces the stresses in the anchor teeth. This is somewhat different from the results reported by De Assis et al. [43], evaluating the effect of the more invasive osteotomy along line of the lower type of Le Fort on the dental stress. The authors found that this procedure leads to an increase in stress, which can complicate the expansion and cause severe pain [60] compared to a more invasive surgical technique. Notably, however, such differences are likely observed in the results because De Assis et al. considered a larger expansion and used a tooth-borne expander.

On the one hand, osteotomy of the zygomatico-alveolar ridge also has virtually no effect on the value and shape of the midpalatal suture expansion; on the other hand, it leads to a greater expansion at the dental level. This can negatively affect the stability of treatment and cause relapse.

Then again, osteotomy of the zygomatico-alveolar ridge on the both sides of maxilla contributes to a slightly more symmetrical distribution of displacements and involves the bone structures of the alveolar ridge near the anchor teeth and the posterior maxilla into the expansion.

4.2.3. Midpalatal Suture Osteotomy

Midpalatal suture osteotomy leads to concentration of the stresses mainly in the anterior palate and to some decrease in the stresses in the teeth. These results are consistent with the results from Möhlhenrich et al. [39], indicating that the force acting from the expander is directed at spreading apart the halves of the maxilla rather than loading bone tissue and teeth.

This surgical technique also leads to a decrease in the size of the highly stressed regions and the magnitude of plastic strains near the holes for mini-screw in the area of the pterygomaxillary suture and in the contact region between the acrylic base and the hard palate. On the other hand, an additional highly stressed region appears near the incisive foramen, along with significant plastic strains near the osteotomy site.

As a result of midpalatal suture osteotomy, displacements are observed in the entire medial and posterior regions of the maxilla, while the opening of the midpalatal suture increases significantly, which is in agreement with the results obtained by Zawiślak et al. [45]. This may have a beneficial effect on the stability of treatment results. In addition, the expansion takes the shape of a triangle with the base in the posterior palate. This means that no diastema forms as a result of the expansion.

4.2.4. Midpalatal Suture Osteotomy with Osteotomy of Zygomatico-Alveolar Ridge on the Both Sides of Maxilla

If midpalatal suture osteotomy with osteotomy of the zygomatico-alveolar ridge on the both sides of maxilla is performed instead of only the midpalatal suture osteotomy, this leads to an increase in the size of highly stressed regions and an increase in plastic strains near osteotomy sites as well as near the incisive foramen and holes for the mini-screws in the anterior maxilla. On the other hand, the stresses in the teeth are slightly lower.

Midpalatal suture osteotomy with osteotomy of the zygomatico-alveolar ridge on the both sides of maxilla contributes to a more symmetrical distribution of displacements than midpalatal suture osteotomy. This surgical technique also leads to the maximum expansion of the midpalatal suture and the maxilla at the dental level, pointing to maximum flexibility of the maxillary structures. The results obtained correlate with those reported by Dalband et al. [44]. However, we should note that additional osteotomy of the zygomatico-alveolar ridge induces a proportionally greater increase in the expansion value at the dental level (by 24.8–25.8%) than at the midpalatal suture level (by 10.8–16.2%).

4.2.5. Optimal Procedure

It can be concluded from all of the above that midpalatal suture osteotomy might be the optimal scenario for surgical intervention for maxillary expansion in patients with completed facial skeleton growth, since it finds the best balance between achieving the maximum opening of the midpalatal suture and the minimum load on bone structures of the hard palate.

4.3. Configuration of the Expander

Antilla et al. [61] report that reduced bony support of the teeth increases the risk of tipping and extrusion of the anchor teeth during maxillary expansion by the SARME method. Our findings confirm that the proposed novel hybrid-type expander configuration does not induce high stresses in the dental alveoli, which means it does not lead to bone resorption in these regions and does not disrupt the support of the teeth. Aside from that, midpalatal suture osteotomy additionally minimizes the stresses in these regions.

Kaya N., Seker E.D. and Yücesoy T [42] studied the effect of combining three different types of expanders (hybrid, tooth-borne, bone-borne) and five different surgical scenarios on the distribution of stresses and displacements in the maxillofacial region. It was found that a highly stressed region is observed in the anchor teeth in models with a hybrid-type expander, and osteotomy along the line of the lower type of Le Fort does not significantly affect the magnitude of these stresses. However, this surgical procedure leads to an increase in the expansion at the dental level. The results we obtained for the combination of the modified hybrid-type expander and osteotomy of the zygomatico-alveolar ridge on the both sides of maxilla are consistent with those described above.

4.4. Comparison: One-Screw Expander vs. Two-Screw Expander

On the one hand, using the two-screw expander leads to an increase in the size of highly stressed regions and the magnitude of plastic strains near the holes for mini-screws and osteotomy sites. On the other hand, it leads to a decrease in stress in the anchor teeth. Therefore, using the two-screw expander leads to a redistribution of stresses from the teeth to the hard palate.

As for displacements, unlike the one-screw expander, the two-screw expander produces a larger expansion of the posterior maxilla. In addition, using the two-screw expander leads to a greater opening of the midpalatal suture in the cases involving midpalatal suture osteotomy. Finally, the two-screw expander helps to increase the transverse dimensions of the maxilla at the skeletal level more than at the dental one.

Thus, the two-screw expander is more effective in terms of maxillary expansion values and the stability of the treatment results. It should be borne in mind however that its drawback is increasing the highly stressed regions and the magnitude of plastic strains near the holes for mini-screws and osteotomy sites, which in turn increases the risk of bone resorption.

4.5. Comparison: Expander Positioned Parallel to the Palate vs. Expander Positioned Horizontally

Changing the position of the expander does not affect the distribution and magnitude of stresses as well as the distribution of displacements and the expansion value. The sole difference in the effects induced by these positions of the expander is that the horizontal position contributes to a more symmetrical expansion of the maxilla. If the expander is positioned parallel to the hard palate, larger displacements are observed on the lower side (in the frontal plane) of the maxilla. Thus, the expander can be positioned differently depending on the degree of symmetry in the patient's maxillary deformity.

4.6. Research Limitations and Future Research Directions

The accuracy of FEA results depends heavily on the accuracy of the model used. Our study deals with biomechanics, always involving certain inaccuracies and uncertainties (in material properties, geometry, loading and boundary conditions). Conversely, the finite element model is a stable system, implying that a small deviation in the initial data leads to small deviation in the results. Furthermore, the conclusions in this study are based on the differences in the simulation results rather than on absolute values of the quantities. Therefore, it is reasonable to use the model built within the adopted framework to achieve the goals set out in the paper.

However, we assumed that elements have isotropic properties, while in reality the cranial bone is anisotropic. It is reasonable to account for this circumstance in further studies.

Another limitation of this study was that an expansion of 0.25 mm was simulated, corresponding to a quarter-turn of the screw. The changes in maxillary bone structures that occur in the early stages of expansion are very important, but additional study of subsequent stages is also of scientific interest.

The developed digital model of the maxillary expansion operation can be significantly improved in future studies by introducing the ossification of midpalatal suture into the model after the required expansion value is reached.

5. Conclusion

We carried out comparative analysis of the total expansion and stress level in the maxilla of the patient with completed facial skeleton growth with 0.25 mm screw expansion using various MISMARPE techniques. A model of a modified hybrid-type expander was used in two configurations, namely, with one expansion screw and with two expansion screws. We also evaluated the influence of the expander's positions on the results (parallel to the hard palate and horizontal). A case without surgical intervention and three different minimally invasive surgeries were considered: midpalatal suture osteotomy, osteotomy of zygomatic alveolar ridge on the both sides of maxilla and midpalatal suture osteotomy with osteotomy of zygomatic alveolar ridge on the both sides of maxilla. We can conclude that the optimal approach is expansion of the maxilla with midpalatal suture osteotomy, combined with a two-screw expander. The opening of the midpalatal suture achieved by this method amounts to 58.0–59.3% of the total expansion of the screw. The choice of the expander position is largely dictated by the specific patient's anatomy. However, it should be borne in mind that the risk of bone resorption persists even with this technique due to the presence of highly stressed regions and local plastic strains near the holes for mini-screws, the osteotomy sites and the incisive foramen. In conclusion, our findings can prove valuable for doctors deciding which scenario of surgical intervention and expander configuration would be more appropriate for a particular patient.

Author Contributions

O. Shosheva designed the research methodology, did the investigation, performed data curation, prepared graphical materials, participated in the results' validation process and carried out the formal analysis; M. Zhmaylo designed the research methodology, performed data curation, prepared graphical materials and participated in the results' validation process; L. Maslov designed the research methodology; A. Borovkov participated as the supervisor and the project administrator; N. Vishneva designed the analysed appliances, participated in the results' validation process and carried out the formal analysis; A. Lanina designed the analysed appliances; A. Yaremenko designed the analysed appliances and participated as the supervisor. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

Acknowledgments

Not applicable.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

Funding

The research is funded by the Ministry of Science and Higher Education of the Russian Federation as part of the World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2022-311 dated 20 April 2022).

Data Availability Statements

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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ORCID iD

Shosheva Olesya https://orcid.org/0009-0005-8081-7671
Zhmaylo Mikhail https://orcid.org/0000-0002-7575-2958
Maslov Leonid https://orcid.org/0000-0002-7423-3996
Borovkov Alexey https://orcid.org/0000-0003-3177-0959
Vishneva Nataliia https://orcid.org/0000-0001-9186-5277
Lanina Anastasiia https://orcid.org/0000-0002-4501-2166
Yaremenko Andrey https://orcid.org/ 0000-0002-7700-7724

How to cite this article: Shosheva O. et al., Assessment of Maxillary Expansion Techniques by means of 3D Elastoplastic Finite Element Static Simulation, *J. Appl. Comput. Mech.*, 11(3), 2025, 715-737. https://doi.org/10.22055/jacm.2024.47055.4653