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THE ROLE OF MECHANICAL FACTOR IN ORTHOPEDIC TREATMENT OF CONGENITAL PALATE CLEFT IN CHILDREN

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Abstract: An objective of this study is to provide an adequate explanation for the role of mechanical factor in the orthopedic reconstruction of congenital palate cleft in children taking into account the growth strains. Consideration is given to an orthopedic remodeling technique used at the All-Russian scientific-practical centre of medical-social rehabilitation “Bonum” (Ekaterinburg, Russia). To provide biomechanical grounds for this technique a mathematical model has been developed, which describes the behavior of the hard palate fragments during orthopedic reconstruction. In order to find an approximate solution to the differential problem the finite element method is combined with the variational formulation of the initial differential problem defined in [1]. The results of numerical calculations allow us to estimate the mechanical action of orthopedic palate on the hard palate fragments. It has been also found that the factor of crucial importance is the relationship between the contact pressure and the size of the plate and fragment contact zone as well as the direction of pressure. Account of growth strains depending on stresses allow to explain turn of palate fragments, it fails to explain which one otherwise.

Key words: dentofacial biomechanics, orthopedic treatment, hard palate cleft, mathematical model, mechanical action, growth strain

Introduction

Nowadays the need of lending specialized aid to children with congenital maxillary defects is the problem of particular concern to physicians all over the world. With the establishment of rehabilitation and health centers and regional and municipal clinics at medical institutes for such children, an urgent aid to neonates with congenital maxilla defects can be provided immediately at maternity home. This also extends the possibilities for designing effective methods of subsequent treatment, which is an effective combination of different therapeutic and surgical-cosmetic measures (early orthopedic reconstruction of abnormally developed maxilla, uranoplastic surgery) aimed at rehabilitation of preschool-age children.

According to available statistics on the rate of birth of children with congenital dentofacial defects, one of 1016 normal newborns in the West Ural region suffers from such a pathology.

The main stage in the treatment of congenital maxillary defects is the employment of orthopedic apparatus which exerts a mechanical action on the separated sides of the cleft. From the biomechanical viewpoint the understanding of this stage is still far from complete and is solely based on the empirical experience and subjective idea of the orthopedic interfere. The development of biomechanical grounds for orthopedic remodeling of the palate cleft is an urgent practical problem in the sense that they provide objective criteria for the choice of individual orthopedic apparatus for each patient and refinement of the existing treatment methods.

Our work is directed towards studying the biomechanical interaction of the separated palate fragments with the orthopedic apparatus. In this investigation, we employ methods of mathematical modeling to acquire an objective information about the effect of mechanical factor on the reconstruction of hard palate fragments.

The simplest mathematical model for describing the behavior of the separated palate fragments taking into account the growth deformation has been first proposed in [2, 3]. In these works, the palate fragment is viewed as a growing cantilever flexible beam. Based on this model and experimental data showing the variation of the palate fragment configuration (control-diagnostic models of patients) we estimated the material constants (the growth parameters) of the growing bone tissue of the hard palate.

In a more recent paper [1] the proposed mathematical model of growth deformation was refined to completely allow for the influence of the mechanical factor.

In the present work, we introduce the technique developed at the All-Russian scientific-practical centre of medical-social rehabilitation “Bonum” for rehabilitation of children and teenagers with congenital dentofacial pathology and serious speech disorders and discuss the results of studying the mechanical action of the orthopedic apparatus on the palate fragments.

Method of orthopedic treatment of congenital palate cleft

The most essential stage of this method is the application of orthopedic plate to separate the nasal and oral cavities and exert mechanical action on the palate fragments. In such a way the fragments are subjected to pressure produced by the adhesion force of the applied plate and the work of a strong muscular masticatory organ - the tongue (Fig.1). Furthermore, the plate prevents the tongue from penetration to the cleft and, as clinical observations show, causes decreasing of the cleft. The plate closely copies the shape of the alveolar process connection with the palate fragment and is confined in the oral cavity due to adhesion in the contact zone. During this stage of treatment the ends of the palate fragments remain free, so that they can easily change their shape with the displacement from the nasal to oral cavity.

The role of mechanical factor in this method is played by the orthopedic plate, which exerts pressure on the basis of under-developed palate fragments just at the place where the alveolar processes are transformed into palate fragments. This anatomical articulation is an

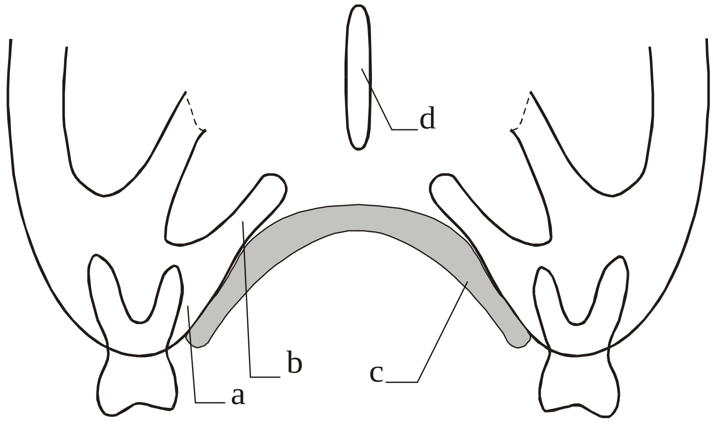


Fig. 1. Schematic representation of two-sided cleft and orthopedic plate:
a) - alveolar process, b) - palate fragment, c) - orthopedic plate, d) - nasal plate.

active zone of maxilla growth [4], and therefore mechanical disturbance of this zone effects the growth processes.

The above method is applied to breast-fed babies. The treatment is normally started at the age of three months, which ensures the essential improvements already in six months (Fig.2, 3).

In all examined cases the early treatment leads to a visible growth of the palate fragments and a change in their position: there occurs an appreciable displacement of the fragments from the nasal to oral cavity. Note however that the experience of physicians specialized in this field suggests that the fragments need not be strictly horizontal. In general this position is non-physiological [5] and depends on the anatomic peculiarities of an individual person.

The clinical fact that the fragments change their position displacing from the nasal to oral cavity has not verified from the biomechanical viewpoint and seems unclear. Therefore our main focus here is to provide mechanical substantiation of the processes occurring in the bone tissue of the palate fragments.

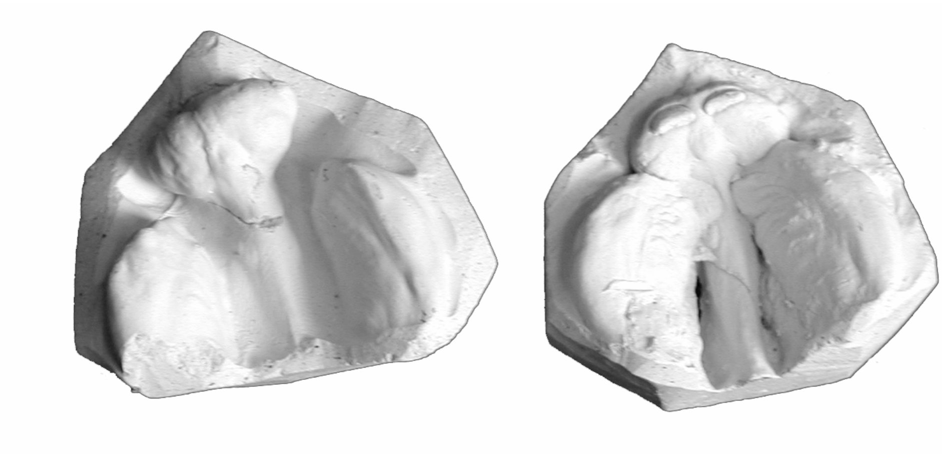


Fig. 2. Control-diagnostic models of patient with congenital two-sided cleft of the upper lip, alveolar process and hard palate at the beginning (12.10.98) and at the end (17.05.99) of treatment ("Bonum").

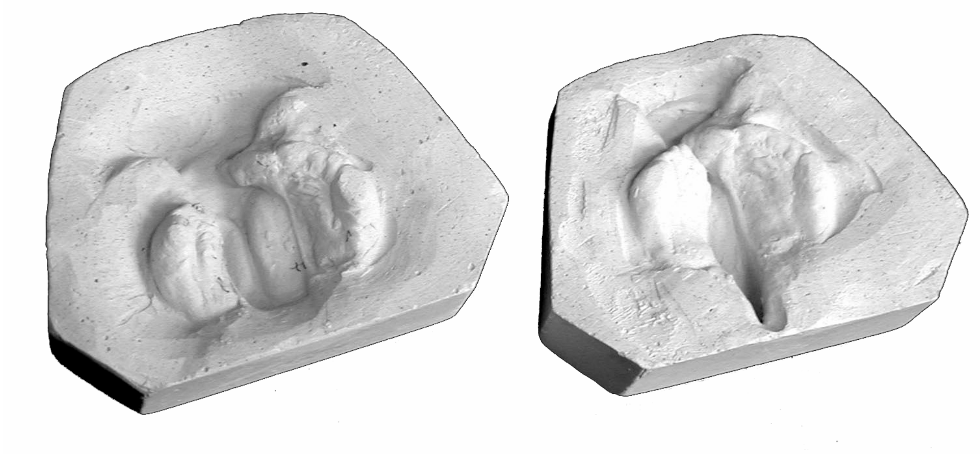


Fig. 3. Control-diagnostic models of patient with congenital two-sided cleft of the upper lip, alveolar process and hard palate at the beginning (20.06.89) and at the end (12.09.89) of treatment ("Bonum").

Mathematical formulation of the problem on biomechanical reconstruction of palate fragments

Here a mathematical model is proposed to describe the behavior of children's hard palate with congenital cleft exposed to mechanical action of the orthopedic apparatus taking into account the growth strains. A general mathematical formulation of the problem on the deformation of growing elastic body has been described in detail in the earlier work [1]. This problem is defined by the following basic equations:

1. the equilibrium equation

,
$$\nabla \cdot \tilde{\sigma} + \boldsymbol{F} = 0, \ \forall \boldsymbol{r} \in \boldsymbol{\Omega} \tag{1}$$

2. the kinematic relations

$$\tilde{\xi} = \frac{1}{2}(\nabla \boldsymbol{v} + \nabla \boldsymbol{v}^{\boldsymbol{T}}), \ \forall \boldsymbol{r} \in \overline{\boldsymbol{\Omega}}, \tag{2}$$

3. the constitutive relations

$$\tilde{\xi} = \tilde{A} + \tilde{\tilde{M}} : \tilde{\sigma} + \frac{d}{dt}(\tilde{\tilde{N}} : \tilde{\sigma}), \tag{3}$$

where $\tilde{\xi}^g = \tilde{A} + \tilde{\tilde{M}} : \tilde{\sigma}$, $\tilde{\xi}^e = \frac{d}{dt}\tilde{\varepsilon}^e = \frac{d}{dt}(\tilde{\tilde{N}} : \tilde{\sigma})$,

4. the boundary conditions

$$\begin{aligned} &\boldsymbol{v} = 0, \ \forall \boldsymbol{r} \in \boldsymbol{S}_v, \\ &\boldsymbol{n} \cdot \tilde{\sigma} = \boldsymbol{p}, \ \forall \boldsymbol{r} \in \boldsymbol{S}_\sigma, \end{aligned} \tag{4}$$

5. the initial conditions

$$\tilde{\sigma}(\boldsymbol{r}, 0) = 0. \tag{5}$$

In equations (1)-(5) $\tilde{\boldsymbol{\sigma}}$ is the stress tensor, $\tilde{\xi}$, $\tilde{\xi}^e$, $\tilde{\xi}^g$ are the tensors of total, elastic and inelastic (growth) strain rates, respectively, $\boldsymbol{v}$ is the velocity vector of the medium, $\tilde{\tilde{N}}$ is the tensor of elastic coefficients, $\tilde{A}$ is the tensor characterizing the proper growth of the material (in the absence of stresses), $\tilde{\tilde{M}}$ is the tensor responsible for the effect of stresses on the growth strain, $\boldsymbol{\Omega} \in R^3$, $\overline{\boldsymbol{\Omega}} = \boldsymbol{\Omega} \bigcup \boldsymbol{S}$, $\boldsymbol{S} = \boldsymbol{S}_v \bigcup \boldsymbol{S}_\sigma$, part of the boundary $\boldsymbol{S}_v$ is subjected to kinematic boundary conditions and $\boldsymbol{S}_\sigma$ is subjected to forces.

As in the previous work [1] we have adopted several assumptions to simplify the form of the constitutive relations (3). In particular, the rate of the growth strain is written as

$$\tilde{\boldsymbol{\xi}}^g = A\tilde{g} + M\tilde{\boldsymbol{\sigma}}, \tag{6}$$

where $\tilde{g}$ is the metric tensor, *A* and *M* are the time independent growth parameters.

In calculations one need to take into account the fact that the palate fragment consisting of pliable cartilaginous tissue is connected with more rigid bone structure (alveolar process). According to relation (6) the parameter *M* should be different for each domain. Clearly, a response of more rigid structure (alveolar bone) to the applied stress is inessential, and hence the growth parameter *M* responsible for the stress effect on the growth processes will be negligible. The following calculations have been made under the assumption that *M*=0 in the zone of the alveolar bone. Since the variation in the stress state causes a marked reaction of the pliable cartilaginous basis of the palate fragment, the second term in the constitutive relations (6) essentially contributes to the growth processes and actually determines the behavior of palate fragments.

The calculation scheme with the defined boundary conditions is shown in Fig.4.

The alveolar process and plate fragment are designated as $\boldsymbol{\Omega_1}$ and $\boldsymbol{\Omega_2}$, respectively. In addition, the classical kinematic boundary conditions provides reaction to the natural material growth. Therefore in our consideration the boundary $\boldsymbol{S_v}$ of domain $\boldsymbol{\Omega_1}$ is assumed to be fixed

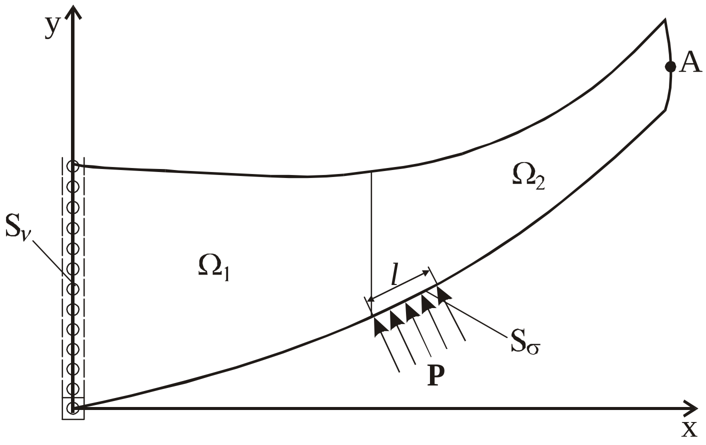


Fig.4. Computational scheme: ⊡ – v_x=v_y=0, |○| – v_x=0, Ω_1 is the region of proper growth (M=0), Ω_2 is the region of stress dependent growth (M=0.08 $mm^2/(g\ month)$), l is the contact region (mm).

as shown in Fig.4. Due to the fact that the bone basis of the fragments is covered by a thin layer of soft tissue we take into account only the normal force **P** transferred by the plate.

Numerical modeling of fragment reconstruction

The developed mathematical model has been used to investigate the influence of the value of the contact pressure and the size of the contact zone on the variation of the fragment configuration. The effect of mechanical forces on the basis of the hard palate fragments was examined over the period of 6 months (t_{end}). The problem is solved as a plane-strain one. An approximate solution to differential problem (1)-(5) has been found using the finite element method in combination with the variational formulation of the initial problem defined in [1].

The parameter of proper growth A in relation (6) was defined from the direct measurements of the control-diagnostic models at the beginning and end of treatment. The average value of the growth parameter obtained from the control-diagnostic models measurements in three patients was $\langle A \rangle$=0.02 month^{-1}, which actually coincides with the estimate of this parameter obtained from control-diagnostic models of differently treated patients [6].

The value of the parameter M defined from the comparison of calculated and clinical data was set to equal to 0.08 mm^2/(g·month). The elasticity module E=500000 g/mm^2 and the Poison's ratio ν=0.3 were taken from [7].

Fig. 5 and Fig. 6 show the displacements u_x and u_y of point A (Fig.4) for different contact regions l and force values $\mathbf{p}(t)=\mathbf{P}$, $t \in [0, t_{end}]$. The displacement u_x characterizes the cleft closure and u_y does the change in the fragment position. The dots show the calculated values and the solid lines are obtained by the least squares approximation using the license software of computer algebra MAPLE V.

The restriction on the maximum value of the force P=20 g corresponds to the maximum possible stress, which can survive the living tissue before the necrosis develops [6].

Fig.7 gives the variation of the fragment configuration in the time of treatment t_{end}: a) without orthopedic apparatus; b) with application of the orthopedic apparatus.

The compression stresses shown in Fig. 8, 9 are generated by the apparatus in the contact region and locally suppress the growth of the palate fragment at its basis. The growth of the material in this region in the direction of x-axis slows down. Hence, the material fibers over the local region of compressive stresses σ_x elongate more rapidly than within this region. Therefore there occurs a fragment bend, which coincides with the clinical results and explains them in terms of growing continuum mechanics.

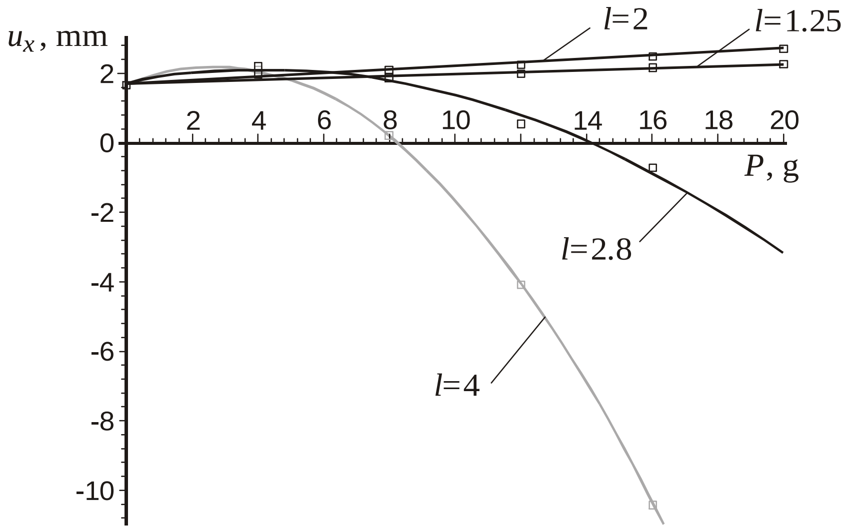


Fig.5. Horizontal displacements of point A (Fig.4) at the end of the fragment for different contact regions *l* (mm).

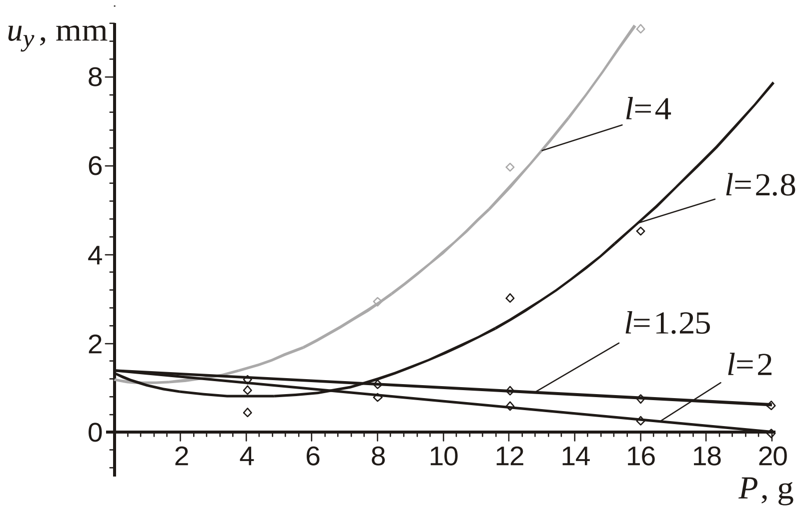
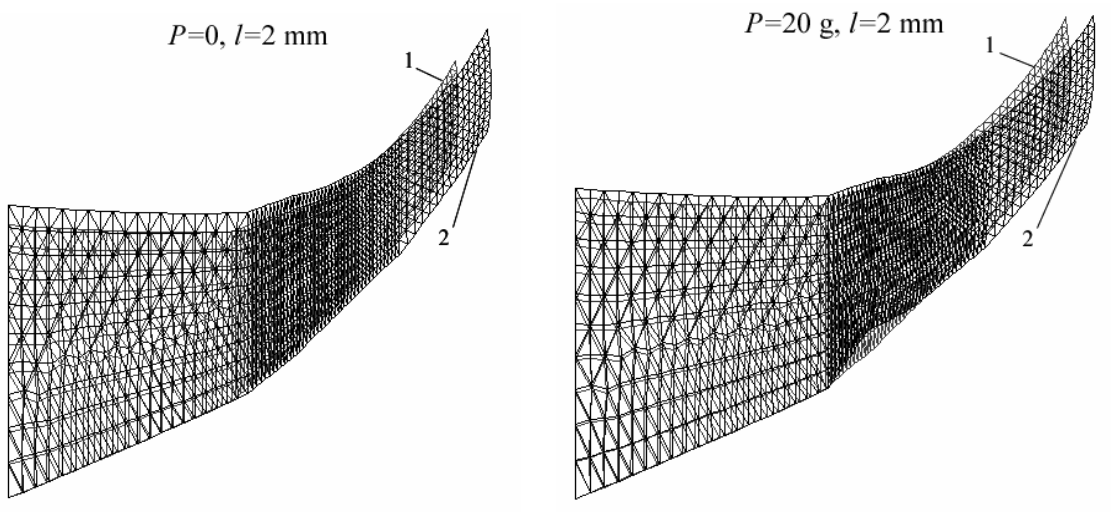


Fig.6. Vertical displacements of point A (Fig.4) at the end of the fragment for different contact regions *l* (mm).



a) b)

Fig. 7. Variations of fragment configuration:
a) without apparatus; b) with the use of apparatus in the case of maximum contact pressure.

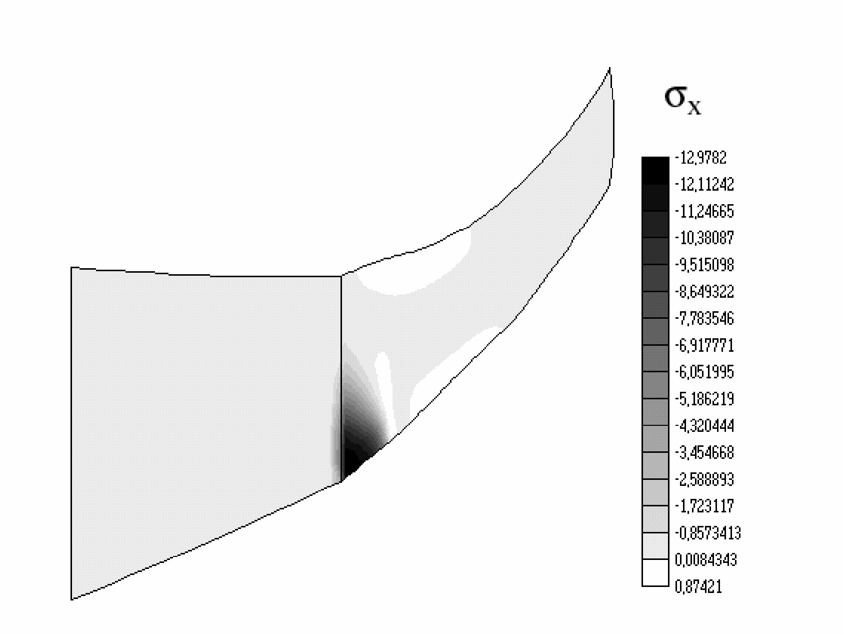


Fig. 8. Component of stress tensor σ_x (g/mm^2) at pressure P=12 g.

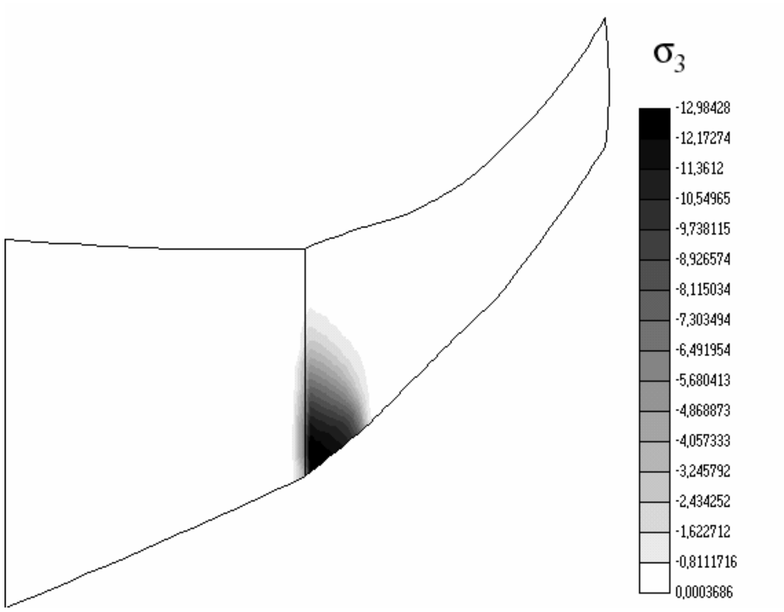


Fig. 9. Third principal value of stress tensor at pressure P=12 g.

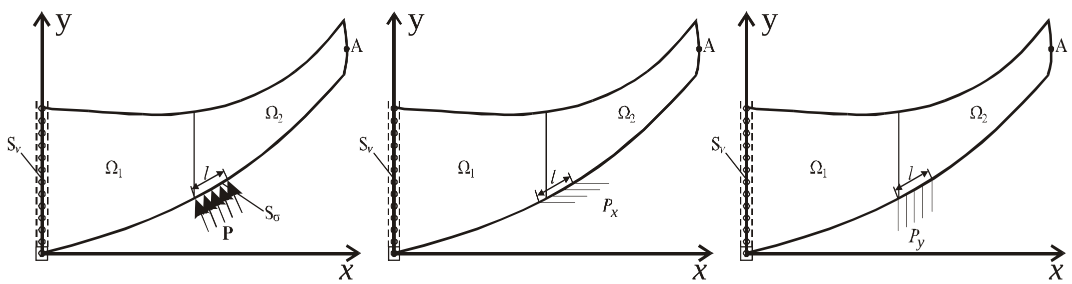


Fig. 10. Three different pressure directions in the contact zone l=2 mm: a) $P=P_n$ (the force is normal to the contact zone): b) $P=P_x$ (the force is directed along the x-axis); c) $P=P_y$ (the force is directed along the y-axis).

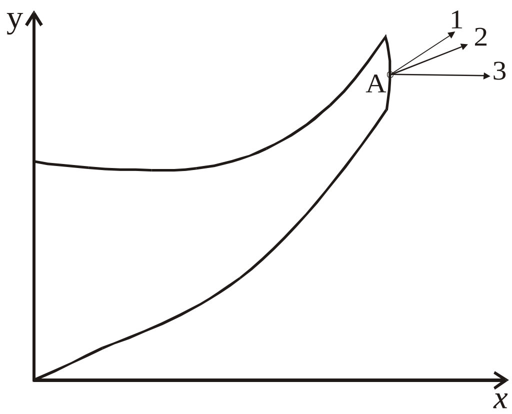


Fig. 11. Displacements **u** of the point A for three directions of the contact pressure: 1 – $\mathbf{u}|_{P=Py}$; 2 – $\mathbf{u}|_{P=Pn}$; 3 – $\mathbf{u}|_{P=Px}$.

Table 1. Values of displacements of point A.

P	*Value P* (g)	u_x (mm)	u_y (mm)	*u* (mm)
P_y	8	1.75	1.20	2.12
P_n	8	2.10	0.79	2.24
P_x	8	2.56	-0.03	2.56

Furthermore the calculations show the influence of the direction of the contact pressure (Fig. 10) on the behavior of the fragments. The corresponding force components are assumed to be equal to 8 g.

The Fig. 11 demonstrates displacements **u** of the point A for three different pressure directions in the contact zone over the time of treatment t_{end}. It is readily seen that the effect of the local compression force P_x on the fragment bending is greater than that of the normally directed force P_n. In the zone of action of the negative force P_x the growth of the bone tissue is locally suppressed, whereas in the remaining region the conditions of natural growth are preserved. Therefore in this region the bending and growth of the fragment occur in the direction of the x-axis. In this case the displacement **u** of the point A is greater than the same displacement under the action of the force P_n (Table 1). This mechanical factor is expected to serve as a basis for designing orthopedic structures. The vertical pressure P_y produces unfavorable effect on the growth and bending of the fragment (the fragment experiences an upward displacement). From the performed calculations it follows that the conclusion that the direction of the contact pressure has a considerable effect both on the growth processes of the palate fragments and their behavior.

Table 1 gives the value of displacements of the point A for three directions of the contact pressure.

Results and discussion

The method of orthopedic treatment of maxilla defects used at the All-Russian scientific-practical centre of medical-social rehabilitation "Bonum" (Ekaterinburg, Russia) has proved to be rather effective and to yield good results over a period of several years (Fig.2, 3). This method has the advantage that the orthopedic plate can be remodeled over the whole period of treatment, which ensures a tighter contact of the plate with the fragment basis and creates favorable conditions for a free growth of the fragment ends. However, there is still a need in biomechanical substantiation of this method. Determination of reliable biomechanical criteria will allow physicians to effectively control the shape of the plate for the benefit of the treatment process on the whole.

The results of our investigations allow us to estimate the mechanical effect of the orthopedic apparatus on the basis of the palate fragments. It has been found that the pressure of the plate on the palate fragment basis inhibits the growth of the fragment bone tissue only in the contact zone. The remaining region is kept intact, which ensures necessary conditions for normal physiological growth of the fragment ends (Fig. 8, 9). Due to a constrained local growth, the palate fragments are gradually displaced to their normal position (Fig. 7b).

The results of calculation have shown that a control of the contact region has a twofold effect: it secures a free growth of the fragment ends and adds to the efficiency of the mechanical action. It is also obvious that the relationship between the size of the contact zone and the value of the contact pressure is the crucial factor of this treatment (Fig. 5, 6) as well as the direction of pressure (Fig. 11).

It should be noted, however, that we need to perform additional investigations to define some other model parameters (the value of the material constant M in the constitutive relations, the value of forces acting on the plate P, and periodicity of mechanical action).

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РОЛЬ МЕХАНИЧЕСКОГО ФАКТОРА ПРИ ОРТОПЕДИЧЕСКОМ ЛЕЧЕНИИ ВРОЖДЕННОЙ РАСЩЕЛИНЫ ТВЕРДОГО НЕБА У ДЕТЕЙ

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Наши исследования направлены на установление качественных и количественных закономерностей поведения расщепленных небных фрагментов у детей при проведении ортопедической реконструкции с целью выявления основных биомеханических закономерностей процесса лечения. Развитие биомеханической теории ортопедической реконструкции является актуальной и практически значимой задачей как в части обоснования выбора ортопедического аппарата, так и в совершенствовании самих методик лечения. Данная работа посвящена изучению биомеханических закономерностей реконструкции небных отростков вследствие механического воздействия ортопедической пластинки, применяемой в научно-практическом центре "Бонум" (г.Екатеринбург). Исследование выполнено с помощью методов математического моделирования с целью получения объективных данных о влиянии механического фактора на реконструкцию небных отростков. Ранее нами были сформулированы дифференциальная и вариационная постановки задачи биомеханического поведения небных фрагментов с учетом ростовых деформаций. В данной работе изучалось влияние на изменение конфигурации небного отростка величины и направления контактного давления, области контакта. Результаты численных расчетов показали, что управление областью контакта необходимо не только с точки зрения обеспечения свободного роста окончания отростка, но и эффективности механического воздействия. Также отмечено, что значимым фактором, влияющим на процессы роста небных отростков и их поведение, является направление действия силы. Этот механически установленный факт может быть положен в основу проектирования ортопедических аппаратов с целью улучшения результатов лечения расщелины твердого неба у детей. Библ.7.

Ключевые слова: челюстно-лицевая биомеханика, ортопедическое лечение, расщелина твердого неба, математическая модель, механическое воздействие, ростовые деформации

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