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PREOPERATIVE PLANNING OF CORRECTION OF CRANIAL DEFORMATIONS USING DISTRACTORS

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Abstract: *This paper presents a procedure of computer aided engineer's support of the treatment of craniosynostosis using distractors. The research encompassed morphological measurements of the skull before and after the surgical procedure, the FEM analysis and the assessment of effects of the correction of cranial deformations caused by the premature fusion of the lambdoid suture. The results of simulations enabled a 3D visualization of the surgical procedure using a distractor as well as the determination of optimum parameters of the operation and guidelines for medical doctors*.

Keywords: Craniosynostosis, Distraction osteogenesis, Preoperative planning.

1. Introduction

Developmental defects of the skull are one of the most serious and common issues in both maxillofacial surgery as well as plastic and reconstructive surgery (Cohen et al., 2000, Wolański et al. 2013). Congenital defects related to the structure of the skull include different types of craniosynostosis which consists in the premature fusion of one or more cranial sutures. Taking into account the statistics, this condition occurs in an isolated or complex form in one infant per two thousand infants (Hayward et al., 2004). The process of craniosynostosis treatment begins as early as in the first months of life of the patient and it requires a risky surgical procedure lasting for many hours (Cohen et al., 2000, Hayward et al., 2004, Wolański et al. 2013). Nowadays, the craniosynostosis treatment takes advantage of the state-of-the-art methods of virtual planning of surgical procedures based on computer tomography (CT) images (Wolański et al., 2015, Kawlewska et al., 2017). This research aimed to perform a preoperative planning of the surgical procedure of the correction of the cranial shape defect using distractors.

2. Methods

This work presents a computer aided engineer's support for the surgical procedure including the process of preoperative planning of the cranial shape correction using distractors in a 4-month female infant with diagnosed craniosynostosis. Apart from the segmentation of the head structure and virtual planning of the operation, a numerical model of the skull and distractor was developed within the framework of the computer aided planning of the neurosurgical procedure (Fig. 1).

2.1. Virtual planning of neurosurgical procedure

In the first place on the basis of the patient's CT images, a 3D skull model was generated in Mimics v16.0 software programme and the brain's body was segmented. A geometrical model of the examined person's skull enabled the performance of basic morphological measurements of the skull, such as the length and

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width as well as the volume of the brain before and after the surgical procedure.

In order to carry out the simulation of a virtual correction, it was also necessary to develop a distractor's geometrical model. On the basis of a real-life object, the geometry of the distractor was recreated in a software programme called Autodesk Inventor 2015. The structure of the distractor consisted of two mounting plates, which included holes for self-tapping bone screws and an adjusting screw in a special protective casing as well as an activator.

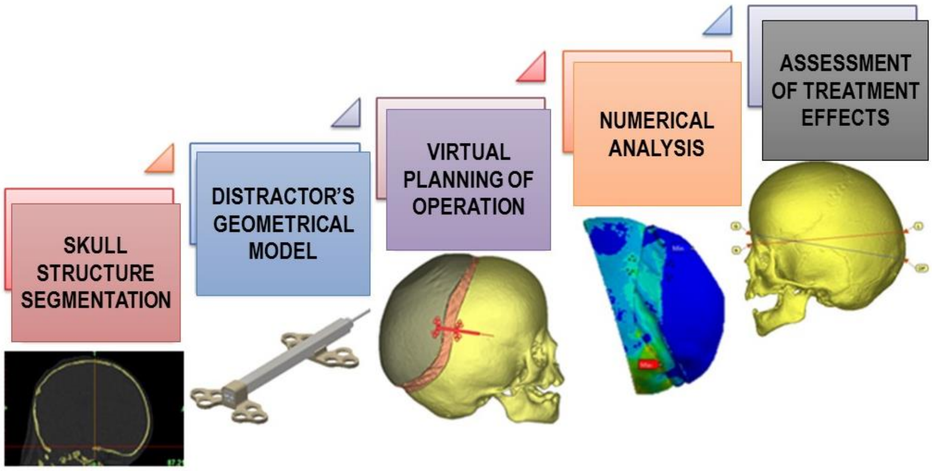

Fig. 1: The course of computer aided surgical procedure of the skull shape correction using distractors.

According to a medical doctor's instructions, the points of mounting the distractor's screws were determined on the segmented model of the skull. Also, the sites of incision were determined on the patient's skull in order to perform virtual osteotomy. Next, the distractor was correctly placed and implemented. Having done the osteotomy, the tissue connecting the separated bones was made, which simulated the development of the bone union. The final stage of the preparation of the skull model consisted in the isolation of the created callus as an individual structure. It enabled the introduction of the developed bone union as well as the anterior and posterior parts of the cranium as separate elements into the Ansys environment in order to conduct a strength analysis. Subsequently, the researchers carried out the simulation of a distraction process lasting 20 days, being developed at a velocity of 1 mm/day. The assessment of the correction was made on the basis of morphological measurements of the skull (anterior and posterior length and skull volume) before the operation and the comparison with the values obtained after the performance of the surgical procedure.

2.2. Preparation of models for numerical analysis

Within the framework of the computer aided engineer's support for the surgical procedure, numerical simulations were conducted to analyze the degree of loads occurring in the bone and callus during the distraction process. Due to the complexity of the model, it was necessary to introduce some simplifications in geometry, namely the facial skeleton as well as a half of the cranial vault were removed. The analyses were performed only for the side where the distractor was located.

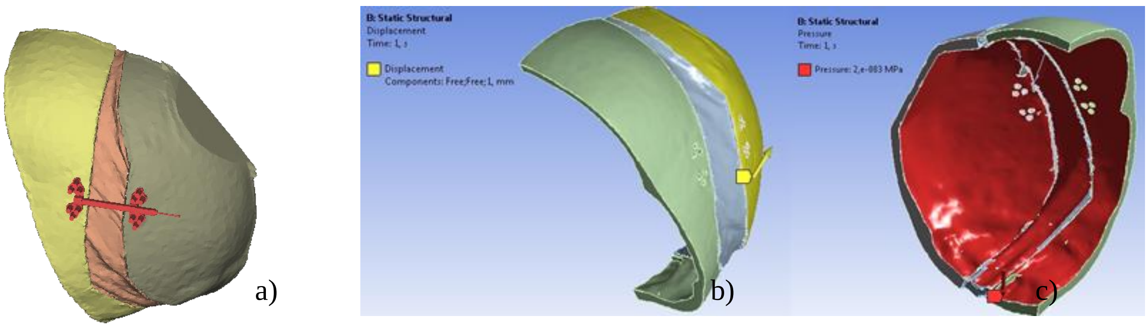

Fig. 2: A simplified model a) view of cranial bones, bone union and distractor, b) boundary conditions – vector displacement in the direction of axis Z, c) boundary conditions – intracranial pressure 15 mmHg on the internal surfaces.

Tab. 1: Material properties of individual elements of the model.

Element	**Young's modulus [MPa]**	**Poisson's ratio**	**Authors**
Frontal bone	1265	0.22	(Wang et al. 2014)
Parietal and occipital bone	1103	0.22	(Wang et. al., 2014)
Callus	130	0.30	(Zreiqat et al., 2015)
Distractor	108000	0.30	(Kromka-Szydek et.al, 2016)

The prepared model was discreted in a software programme called 3-matic using the Remesh module. Then, it was imported to the Ansys Workbench software programme. The whole model consisted of 77679 finite elements of a solid type including 34829 nodes. Individual parts of the model were joined by a bonded contact, making it impossible for the elements to move in relation to one another.

Next, the boundary conditions corresponding to the surgical procedure parameters were set in the model. The created model was fixed onto the anterior surface of the frontal lobe which was deprived of all degrees of freedom. The load consisted in the vector displacement operating in the direction of axis Z of the whole parietal-occipital lobe as well as the intracranial pressure exerting force in the normal perpendicular direction onto the internal surface of the cranial bones (Fig. 2). The simulations were conducted for a displacement of 1 mm and a pressure of 15 mmHg. Individual elements were attributed with proper material properties on the basis of literature (Tab. 1).

3. Results

As a result of the conducted simulation, the researchers obtained the distribution of stresses and strains reduced according to von Mises' hypothesis as well as the resultant displacement vectors occurring in the callus, frontal bone and parietal-occipital bone during the virtual surgical procedure of the correction of the skull deformation using a distractor.

The values of stress in the cranial bones at a forced displacement of 1mm did not exceed 100 MPa, and for the callus it amounted to approximately 30 MPa (Fig. 3). Simultaneously to the analysis of the stress-strain field, the analysis of the distribution of deformations was conducted. The highest value of a deformation amounting to 0.4 mm/mm was observed in the lower part of a newly-formed bone tissue.

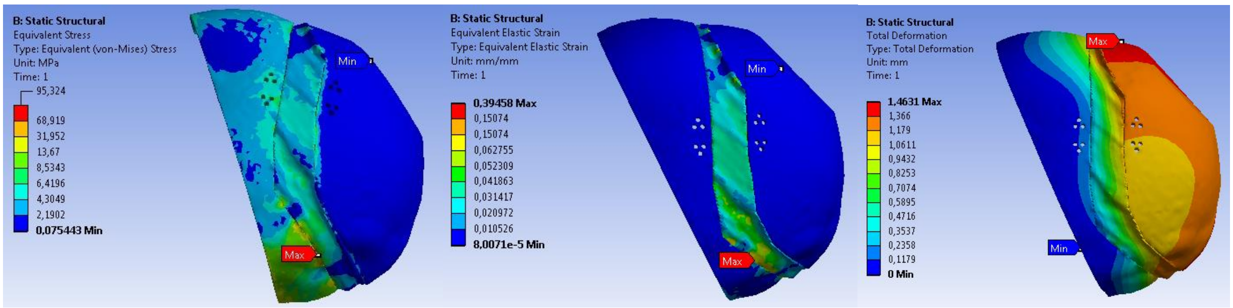

Fig. 3: Distribution of reduced stresses and strains as well as complete deformation.

The analysis of a complete deformation of the system revealed that a maximum displacement of approximately 1.5 mm was obtained on the parietal-occipital bone in the field which was located the furthest from the applied fixation. The obtained distribution of displacements results from the fact that bone elements were provided with directional displacement operating in the axis of the distractor.

In addition to that, the assessment included also the values of stresses in the distractor, which were obtained in the simulation of the surgical procedure of distraction osteogenesis. A maximum stress value amounting to approximately 13 MPa was observed on the junction of the mounting plate and the adjusting screw (Fig. 4). The distractor itself showed no high values of stress which could cause damage to the device made of material Ti-6Al-4V having high strength properties.

The evaluation of the effects of the computer aided preoperative planning of the correction of craniosynostosis was made on the basis of the comparison of the measurements of the patient's skull (anterior and posterior length as well as brain volume) before and after the surgical procedure. An objective assessment was carried out on the grounds of a quantitative analysis of morphometric measurements, which showed the convergence of their values both after the surgical procedure and the virtual procedure of distraction (differences in the results of virtual simulation and real values of the parameters measured after the surgical operation do not exceed 10 %).

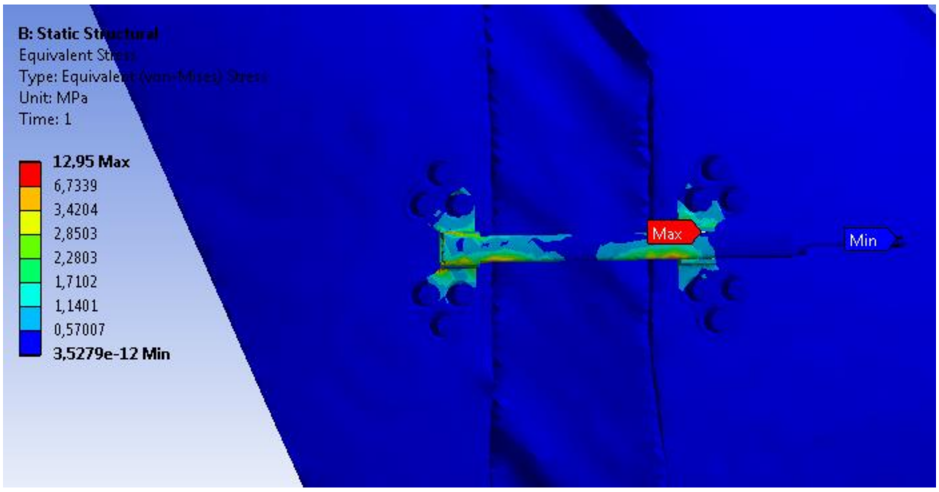

Fig. 4: Distribution of stresses reduced in distractor.

4. Conclusions

Within the framework of the research, a virtual planning of the process of craniosynostosis treatment by means of distraction osteogenesis was performed. The conducted simulations enable the recreation of the applied surgical procedure making it possible for the surgeon to evaluate individual stages of the planned medical operation. A computer aided correction of the defects of the skull shape enables the selection of optimum parameters of the surgical procedure, which shortens the duration of such procedure, increases its efficiency and improves the treatment quality and patients' safety. The application of computer aided engineer's methods supporting the pre-operative planning also opens up possibilities of virtual training in the scope of complex surgical procedures, visualization of the distraction effects as well as the assessment of the tissue damage during distraction osteogenesis.

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