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Biomechanical aspects of preoperative planning of skull correction in children with craniosynostosis

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Craniosynostosis is a birth defect that causes one or more sutures on a baby's head to close earlier than normal. In effect the growing brain determines an abnormal skull shape and, which is more important and more dangerous, it causes an elevated intracranial pressure. The only treatment for children with craniosynostosis is surgical cranioplasty. More extensive procedures yield excellent results, particularly in older children with moderate to severe deformity. However, in children undergoing more extensive reconstructions an essential requirement is blood transfusion. They are also put at risk of complications. In this paper, the authors propose a method of preoperative planning based on three-dimensional modelling and biomechanical investigations. We used Mimics, 3-matic and ANSYS software for the process. The proposed preoperative planning improved the preoperative knowledge of deformation, shortened the time of surgery, and subsequently reduced blood loss during the procedure.

Key words: *biomechanics, craniosynostosis, preoperative planning, 3D-modelling*

1. Introduction

Surgical treatment of craniosynostosis despite the prevalence of the condition and a long history of its treatment still poses a challenging clinical problem. The only treatment for children with craniosynostosis is surgical cranioplasty. From the first attempts at craniosynostosis surgery in the 19th century, a host of surgical procedures have been used for the treatment, ranging from simple suturectomies to extensive calvarial vault correction [1]–[3]. The general rule is to open the premature cranial suture or sutures to provide ample space for the development of the brain, and to enable the skull to expand to normal shape as the brain develops. After a proper surgery, as the brain grows, the skull can expand sufficiently under the sustained stress generated by the brain and serves as the inner surface of the skull through the endocranium. Moreover, after the surgical correction of the skull in craniosynostosis surgery, the bone rigidity of both calvaria and skull base is changed and the stress is redistributed [3]. We know from experience that more extensive reshaping yields excellent results, particularly in older children with moderate to severe deformity [1], [2], [4]. Yet, children undergoing more extensive reconstructions urgently need blood transfusion and are put at increased risk of complications [4].

In 1998, BARONE and JIMENEZ proposed a minimally invasive endoscope-assisted method of treatment for children with craniosynostosis [5]. They found that the method decreased blood loss, operating field, and cut the time of surgery short. Also, the authors were able to present good short- and long-term results after the surgery [5], [6]. There are certain disadvantages of the endoscopic method: a cranial molding helmet has to be worn afterwards for several

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months for 23 hours a day [6], and the procedure can be performed only in children no older than a few months of age [5]. Biomechanical methods provide a very accurate tool for a better understanding of cranial anomalies with the application of advanced 3-dimentional modelling [7], [8], and can be very beneficial in the preoperative planning of such complicated neurosurgical procedures [8], [9], [13].

The purpose of this paper is to propose a model of preoperative planning in craniosynostosis surgery with the application of biomechanical research.

2. Materials and methods

The schema of the proposed procedure of preoperative planning in craniosynostosis surgery is presented in figure 1.

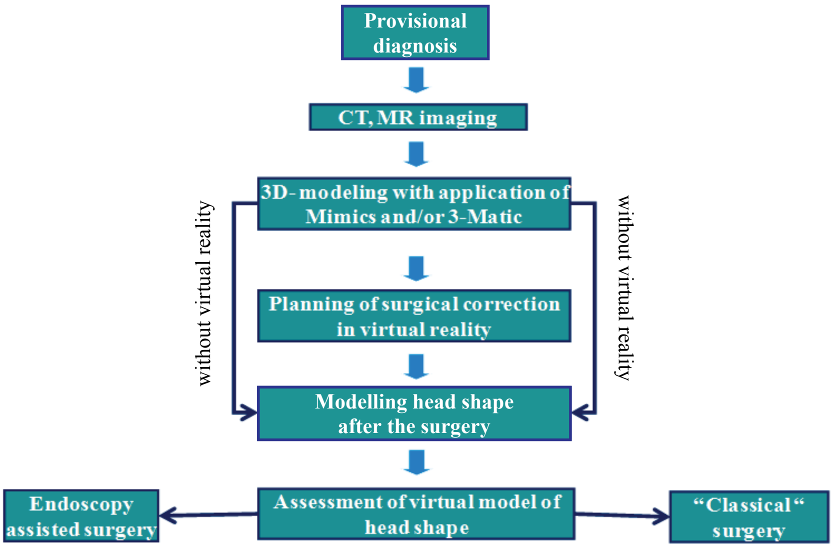

Fig. 1. Preoperative planning schema

2.1. Provisional diagnosis and CT/MR imaging

A provisional diagnosis is often established on the basis of parents' complaints of an abnormal head. Also, a neonatologist or a paediatrician can suspect cranial abnormalities and refer a child to a neurosurgical outpatient clinic. In the previous twenty years, the first stage of diagnostics used to be an X-ray of the skull. Nowadays, the gold standard of imaging is computed tomography (CT) with 3-dimensional reconstructions. In some cases with associated congenital brain anomalies, magnetic resonance imaging (MR) is performed. What is very important, standard CT and MR examinations are used for the process of preoperative planning.

2.2. Three-dimensional model of the skull for children with craniosynostosis

In our paper, children with isolated (non-syndromic) craniosynostosis are presented. We have chosen children with premature closure of sagittal suture and with premature closure of metopic suture as examples of patients suitable for the modelling and treatment processes. Craniosynostosis concerning abnormal premature closure of sagittal suture results in a scaphocephalic head, which is long and narrow with a very specific frontal and occipital bossing. The skull of a child with scaphocephaly is shown in figure 2a. Trigonocephaly means a triangular shape of the forehead with a deformation of the frontal bone and a deformation of the anterior part of the skull base. Moreover, an abnormal position of the orbits is present in children with premature metopic synostosis. The most visible deformations are hypotelorism and rotation of the orbits in the coronal plane. An example of a skull with trigonocephaly is shown in figure 2b.

The morphological analysis was performed with Mimics 14.11 (Materialise, Belgium) software which allows for 3D modelling from a standard conventional

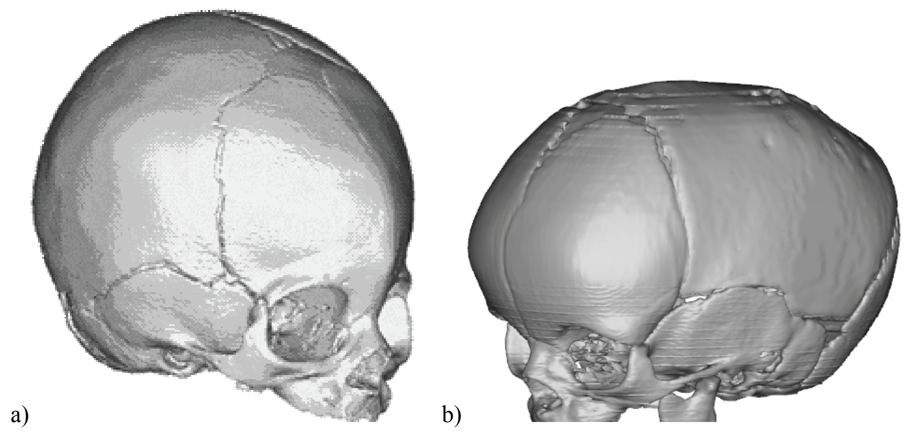

Fig. 2. 3D models of the children's skulls:
a) with metopic craniosynostosis and subsequent trigonocephaly,
b) with premature closure of sagittal suture and subsequent scaphocephaly

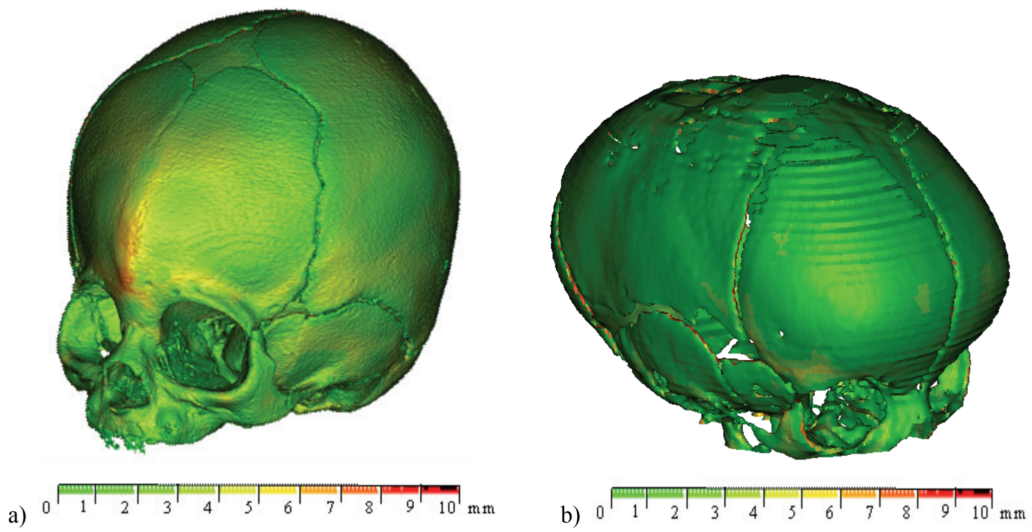

Fig. 3. Wall thickness analysis for a child:
a) with trigonocephaly, b) with scaphocephaly

Table 1. Parameters of wall thickness analysis for children

Analysis parameters	Child with trigonocephaly			Child with scaphocephaly		
Type	Q1	Median	Q3	Q1	Median	Q3
Analysis statistics	0.814 mm	1.374 mm	1.809 mm	1.846 mm	2.336 mm	2.726 mm
Mean – standard deviation	1.376 mm ± 0.913 mm			2.339 mm ± 1.051 mm		

CT. To evaluate the abnormalities, numerous measurements were carried out based on 62 anatomical points and their distances. Also, a comparison of the anthropometric data on the right and left sides, including anthropometric angles and indices, was made. The whole process of morphological analysis is described in our previous papers [8], [9].

The next step of preoperative planning is a wall thickness analysis. The process is possible with the application of 3-matic (Materialise, Belgium) software. The skull thickness analysis for a child with trigonocephaly is presented in figure 3 and table 1.

2.3. Virtual planning of surgical correction

The application of the aforementioned software allows us to devise in an easy way a preoperative plan for surgery. Based on the analysis of the morphological abnormalities, it is possible to plan an appropriate and optimal method of cutting the bones. For the sake of further analysis, three-dimensional models of the skull have to be generated. The next step is to separate regions of the same material properties. This is done by creating masks that comprise regions of the same properties and erasing superfluous information coming from the adjacent parts. In the next step, a three-dimensional surface mesh is created on the basis of the first mask. It is possible to control the parameters used during the mesh generation. It is, therefore, easy to control the quality of the object. Then, the material properties (density, Young's modulus, Poisson's ratio) of bone structures are defined. In every case, the properties depend on the radiological density in Hounsfield Units (HU). It is also possible to generate a model of non-homogeneous material properties by the determination of corresponding material groups. After the generation of a three-dimensional surface model, it is necessary to mesh it by means of finite volume elements. It is done with the use of a system in which finite element analysis can be carried out. In our practice, both Mimics and 3-matic software are used to create the mesh. The plans of craniectomies were created in Mimics software, depending on the deformation type. In figure 4, preoperative plans for trigonocephaly and scaphocephaly are shown.

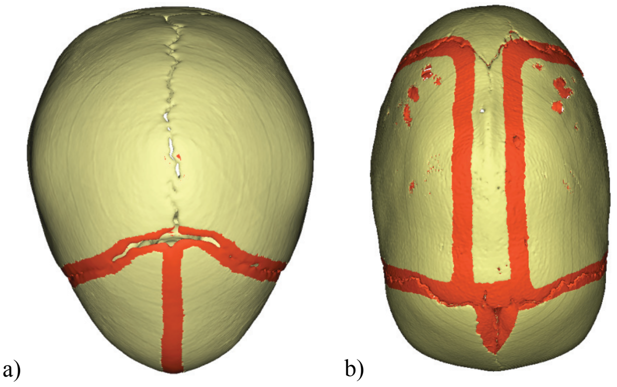

Fig. 4. A preoperative plan for a minimally invasive endoscopic approach: a) plan of the osteotomies for a trigonocephalic skull, b) a scaphocephalic skull with places of osteotomies

In the final process, a detailed plan for the surgery is developed to be taken into the operating theatre (figure 5).

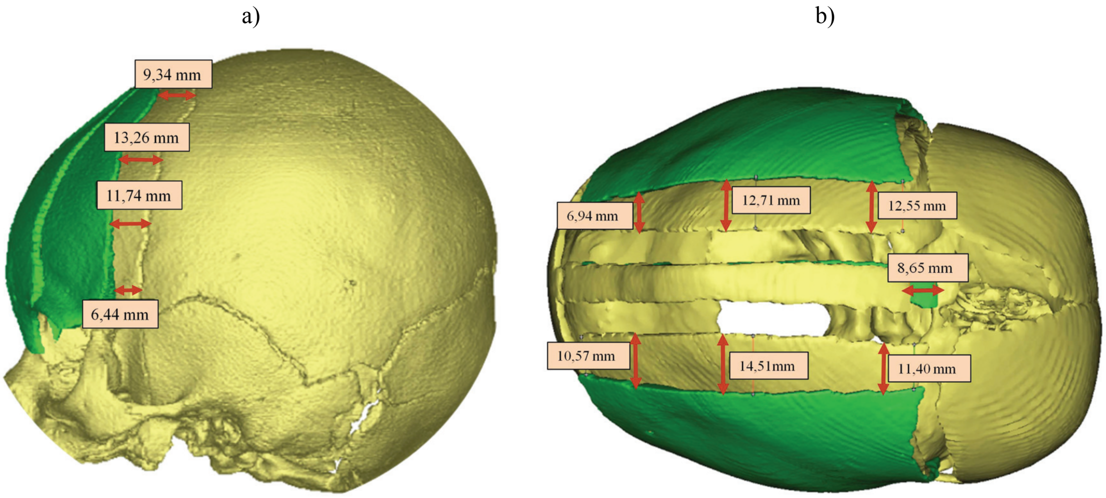

Fig. 5. Part of preoperative plan for endoscopic surgery: a) trigonocephaly, b) scaphocephaly

2.4. Modelling of the head shape after surgery

Based on the preoperative plan, it is possible to obtain during surgery the proposed model of the head, which is very important both for medical reasons and for the sake of parents' knowledge necessary for their informed consent for the operation (figure 6).

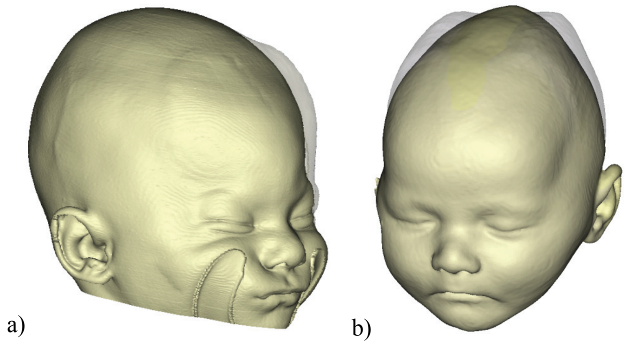

Fig. 6. Planned changes in the head shape after surgery in children with:
a) trigonocephaly, b) scaphocephaly

2.5. Assessment of the virtual model of head shape

The first assessment of the modelling performed is done at the end of the surgical procedure. It is possible to measure the anthropometric distances on the head. Later, the second assessment is carried out on the basis of a follow-up CT scan performed usually one year after the surgery. The software applied allows for postoperative morphometric analysis and partial comparative analysis as well.

3. Results

The devised models with the correction planned are subject to numerical analysis. Durability calculations with the use of finite elements method make it possible to determine the places most at risk of breaking [14]. Such an information allows us to verify the appropriateness of the planned correction, especially for endoscopic procedures. Should such circumstances occur, i.e., should the bones break, it may compromise the validity of minimally invasive surgery, as broken bones make classical surgery inevitable. At this stage of the engineering-assisted planning of skull-correction in children with craniosynostosis, we determine the stresses and deformations of the skull bones which help to determine the risk of breaking.

For the analyzed cases of scaphocephaly and trigonocephaly the generation of finite elements' mesh in 3-matic software is possible with the use of ANSYS software. This allows for a simulation of the planned correction and helps to determine the stresses and deformation of the cranial bones (figure 7, table 2). The analysis of the results received shows that the procedure was planned correctly. The stress values did not exceed admissible values (no breaking shall occur), and the relocations obtained met the expectations.

Table 2. Results of biomechanical analysis

Type of cases	Deformations (mm)	Stress (MPa)
Scaphocephaly	18.22	37.92
Trigonocephaly	19.26	40.56

The last stage of the preoperative planning consists in making sure whether the incisions will be possible with the use of available endoscopic tools.

We have conducted experimental studies that provide information on the maximum thickness of the skull bones which can be cut by endoscopic instruments. First, the maximum force of fingers tightness and the force of cutting with scissors were determined. The measurement was conducted with the use dynamometer (figure 8). The results received are shown in table 3.

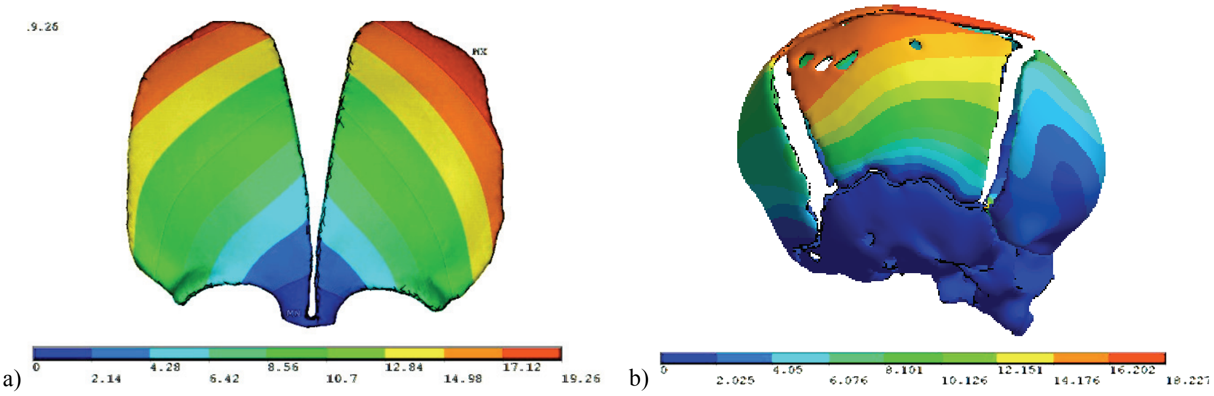

Fig. 7. Analysis of deformations:
a) in the frontal bone in a child with trigonocephaly, b) for the skull in a child with scaphocephaly

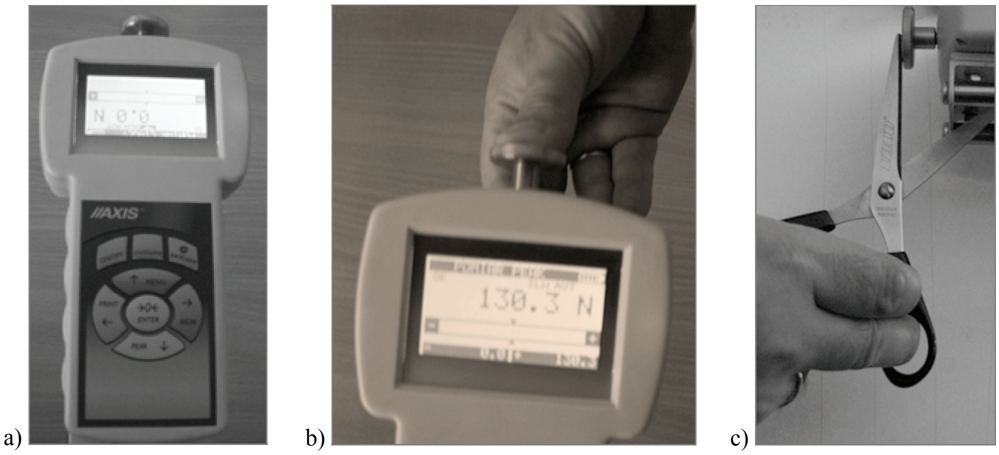

Fig. 8. Dynamometer for the measurement of forces (a), measurement of fingers' loads on scissors (b), measurement of forces during cutting with scissors (c)

Table 3. Measurement of forces for the cutting with scissors

Type of measurement	Mean F (N)	Standard deviation (N)	$F_{\min}$ (N)	$F_{\max}$ (N)
Fingers force on scissors	154.19	22.14	114.00	202.40
Cutting force	70.58	10.61	50.00	86.30

The values of force allowing skull bones to be cut can be determined as follows:

$$P_{\max} = k \cdot R_t \cdot S = k \cdot R_t \cdot g \cdot l \,, \tag{1}$$

where:

$P_{\max}$ – max. force (N),

k – ratio depending on the looseness in the scissors (1.1–1.3),

R_t – shear strength of bone (MPa),

S – area (mm^2),

g – thickness (mm),

l – length of incision made with scissors (mm).

The parameters necessary for assessing the force for bone cutting were determined in experimental tests. The tests on the specimens of skull bones obtained during previous operations were conducted on an MTS insight stand. During the tests the characteristics of children's skull bones were determined with standard experimental methods [8], [10]. The average value of shear strength of a skull bone of a 3-months-old child equals R_t = 5.17 MPa. The material properties of a skull bone depend on children's age. This is due to bone stiffness. The younger the child, the lower the bone stiffness.

Using the same calculation for g = 2 mm, R_t = 5.17 MPa, l = 10 mm, the value of force for cutting the skull bones is:

$$P_{\max} = 1.1 \cdot 5.17 \cdot 2 \cdot 10 = 113.74 \text{ N} .$$

Surgery scissors work like a first class lever with the fulcrum in the middle, the effort (F) on the one side, and the load (P) on the other side (figure 9). The force applied is proportional to the ratio of the length of the lever arm measured between the fulcrum (pivoting point) and the application point of the force applied at each end of the lever. Mathematically, this is expressed by the following equation:

$$P \cdot r = F \cdot R \,, \tag{2}$$

where:

F – effort – applied force (N),

P – load – force of reason (N),

r – radian – short arm (70 mm),

R – radian – long arm (140 mm).

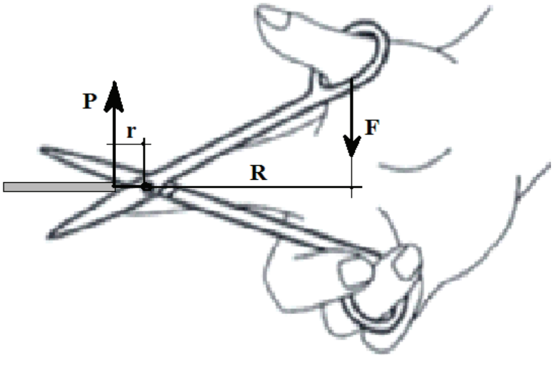

Fig. 9. Equilibrium of forces during cutting with scissors

When distances between forces and human hand forces during cutting are known, it is possible to determine the cutting force F:

$$F = \frac{P \cdot r}{R} \,. \tag{3}$$

In the scissors studied, the arm lengths were r = 70 mm and R = 140 mm. The force needed to cut the bone of the skull equals 56.87 N. This makes up 28.1% of the maximum force of fingers tightness.

$$F = \frac{113.74 \cdot 70}{140} = 56.87 \text{ N}.$$

It is customary to cut not with the ends of the scissors, but at 2/3rds of their length. The cutting force at work there equals:

$$P = \frac{113.74 \cdot 46.6}{140} = 37.86 \text{ N}.$$

The force of 37.86 N makes up 18.7% of the maximal finger force exerted on scissors. We can assume that 2-mm thick bones can be cut with an optimal load of a surgeon hand. In such conditions, cutting would not be responsible for fatigue. Based on the biomechanical experiment, the maximal thickness of bone that can be operated with the endoscopic approach can be calculated as follows:

$$P_{\max} = \frac{F_{\max} \cdot R}{r} = \frac{202.40 \cdot 140}{70} = 404.8 \text{ N},$$

$$g_{\max} = \frac{P_{\max}}{k \cdot R_t \cdot l} = \frac{404.8}{1.1 \cdot 5.17 \cdot 10} = 7.1 \text{ mm}.$$

During the preoperative planning process the analysis of bone thickness provides the knowledge whether it is possible to adopt the minimally invasive approach.

4. Discussion

In neurosurgical and craniofacial centers treating children with craniosynostosis, there is a tendency to individualize surgical approach which allows the best aesthetic outcomes and the lowest reoperation rates. Total cranial vault reconstruction is a major operative procedure, but unfortunately not without morbidity [1], [2], [4], [5], [11]. The new technique combining the endoscopic-assisted approach with the postoperative helmet molding for the treatment of sagittal synostosis has given excellent results. This approach, however, has its disadvantages, i.e., a prolonged need for the postoperative helmet molding and limitations when it comes to treating severe variations in trigonocephaly and scaphocephaly [5], [6]. In the present method of treatment, we wanted to obtain the balance between extensive corrective osteotomies and osteotomies with immediate correction and a minimally invasive endoscopic approach. The application of such a philosophy requires a very good understanding of craniofacial anomalies and the knowledge of the properties of abnormal bones.

Preoperative analysis of bone thickness is crucial in terms of deciding whether the endoscopic cranioplasty will be the best. Endoscopic surgery has brought to the forefront new and significant ergonomic issues relating to the surgical manipulation of tissues. Surgeons performing endoscopy experience significant ergonomic problems, especially finger numbness. Endoscopic instruments work on reduced efficiency and require 4 to 6 times more force than open surgery instruments to complete the same task [12]. Moreover, these endoscopic instruments are generally available in one standard size. That is why wall thickness analysis is a very important part of the preoperative planning process. It allows us to choose the proper method of surgery – endoscopic or open. One of the most crucial points during cranioplasty is the use of appropriate surgical tools. In younger children, with the application of the endoscope the bones can be cut with scissors. In the "classical" open approach, craniotomes and high-speed drills or piezoelectric knives are used. Biomechanical analysis could answer the question whether in a particular case it is possible to cut the bones with scissors and perform the surgery with the minimally invasive method or whether the procedure should be open.

The proposed model of preoperative planning was used for more than a hundred of children with craniosynostosis operated either with endoscopic or open approach. It improved the preoperative knowledge about the deformation, shortened the time of surgery, and, subsequently, reduced blood loss during the procedure. We can conclude that a close cooperation between biomechanics and neurosurgeons improves the efficacy and safety of treatment for children with craniosynostosis. Moreover, the application of biomechanical investigations in the preoperative process allows us to apply new methods of minimally invasive treatment.

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