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Original Articles

Three dimensional finite element biomechanical analysis of unilateral coronal synostosis and reconstructive operation

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ABSTRACT

Objective To establish finite element models of skull, fronto-orbital advancement and fronto-orbital distraction osteogenesis of craniosynostosis, to analyze the mechanical characteristics of skull base and fronto-orbital operation area, so as to guide the later application of distractors.
Methods One 6-year-old male patient with unilateral coronal synostosis was enrolled in October 2015. Three-dimensional (3D) computed tomography (CT) scan of skull was performed. DICOM data was imported into Mimics 17.0 for contour extraction and cranial 3D reconstruction. The skull model was processed by Mimics, Geomagic Studio 12.0, Hypermesh 12.0 and other software to establish a three-dimensional finite element model. The unilateral and bilateral fronto-orbital anterior osteotomy models were simulated respectively. The mechanical analysis was performed at point A in forehead area and point B in temporal area. Three different groups of traction forces were loaded: (1) 50 Newton for point A, 50 Newton for point B; (2) 80 Newton for point A and 50 Newton for point B; (3) 100 Newton for point A and 50 Newton for point B, to obtain the optimized traction force. .
Results Stress analysis was performed on established cranial finite element model, as well as unilateral and bilateral fronto-orbital advancement procedures. The stress distribution of the anterior and middle cranial fossae was found to be concentrated. After unilateral fronto-orbital advancement, the stress of anterior cranial fossa, especially the affected side, was decreased. The stress on both side in anterior cranial fossa was decreased after bilateral fronto-orbital advancement. After force was applied to point A and point B, the optimum deviation result at supraorbital notch point, midpoint of supraorbital margin, frontal temporal point and frontal zygomatic suture point in 3D (Deviation result of X value: -29.4%, -20.5%, -8.6%, -9.3%, Deviation result of Y value: 20.9%, 31.5%, 73.0%, 539.4%; Deviation result of Z value: 4.4%, 1.9%, 0.1%, 11.8) demonstrated the application of traction force can inwardly, downwardly and forwardly move the bone flap. The optimized traction was 80N at point A and 50N at point B by preliminary assessment.
Conclusion The finite element analysis of the fronto-orbital advancement can be used for more accurate preoperative simulation, to clarify the influence of fronto-orbital advancement on craniofacial morphology and development, as well as skull base. It also facilitates surgical decision and predicts the postoperative distraction vectors

KEY WORDS

craniosynostosis; finite element analysis; biomechanical analysis

BACKGROUND

Unicoronal craniosynostosis refers to the craniofacial malformation due to premature osseous closure of lateral coronal suture. The typical clinical symptoms include the flattened and retracted frontal bone, taller and retracted orbit, and sometimes intracranial hypertention and dysfunctions of brain and eyeballs[1,2].

Hardy and Marcal[3] et al. firstly reported a case of three dimentional finite element model (FEM) of a human skull and conducted a static simulation. From then on, FEM became widely used in craniomaxillofacial surgery, which could better analyze the biomechanical properties of the complicated maxillofacial tissue and bring about objective and reliable outcomes. Helping getting rid of the restricts of physical construction and reducing the expenses of animal or clinical experiments, FEM is gradually taking place of conventional biomechanical analyzing models[4]. With the development of computed technology, FEM has extensively used in medical researches.

In October 2015, we planned to establish a FEM of a skull of a 6-year-old unicoronal craniosynostosis patient, simulations of fronto-orbital advancement and fronto-orbital distraction to analyze the craniofacial skull base and the mechanical characteristics of the constructive surgery, so as to guide the application of the tractor.

MATERIALS

One 6-year-old male patient diagnosed of unicoronal craniosynostosis of left side was involved in this study. After excluding systemic diseases and obtaining the ethical verification, three dimensional (3D) computed tomographic (CT) scan(Phillips Brilliance 64 spiral CT , Netherlands Phillips) was underwent and digital imaging and communications in medicine (DICOM) data was received.

METHODS

Data collection and establishment of skull computer-aided design (CAD) model

The DICOM data was input into Mimics 17.0 (Materialise,Leuven,Belgium) and then the contour was extracted. Through the threshold segmentation method in the software, the parameters of the bone window were set to a range from 226 to 4095, the skin was then formed. The whole skull tissue was reconstructed in three dimensions, and the skull tissue was converted into a preliminary three-dimensional geometric surface model by the command of Calculate 3D. The model included the skull, maxilla, zygomatic and other bone tissues. Simultaneously, unilateral fronto-orbital advance osteotomy and bilateral fronto-orbital advancement were simulated. The final data was saved in .STL format, which contained a three-dimensional skull geometric model, a unilateral fronto-orbital and a bilateral fronto-orbital advancement simulation geometric model. (Fig.1)

The STL format data was transferred to the reversal engineering software Geomagic 12.0, and the joints such as coronal suture, sagittal suture, lambdoidal suture, frontosphenoid suture, frontozygomatic suture and alike were respectively depicted on the surface of the skull, and the preliminary 3D skull model was processed to form a point-stage processing. Triangular patches were generated and the model was trimmed to obtain a complete triangular surface model, which simplified the surface details of the skull, forming a solid model in the multi-faceted stage. By performing surface smoothing including commands of removing and deleting nails, reducing noise, eliminating features, a geometric model with a smooth surface was finally achieved.

Establishment and pre-processing of finite element model of skull

Meshing

Generated geomatrical models were imported to Hypermesh 12.0 (America, Geomagic) for division of facial meshes with the control of accuracy and quality of the meshes. The models included skull bone and maxillofacial bones. The skull bone was defined of complex structure comprised of the cortical bone on the both ecto- and endo-cranial surface, the diploic bone of the inner layer and the soft tissue of scalp. The characteristic blocks of skull bone and suture were respectively refined and divided. The nodes were then formed in the boundary of every characteristic block. These blocks were automatically projected onto the geometric model interface to ensure more precise detailed features. The association of the feature blocks can be manually fine-tuned to improve the accuracy of the model and then the surface mesh file was saved. The default parameters of the body mesh model of the system was selected to set the bone structure.

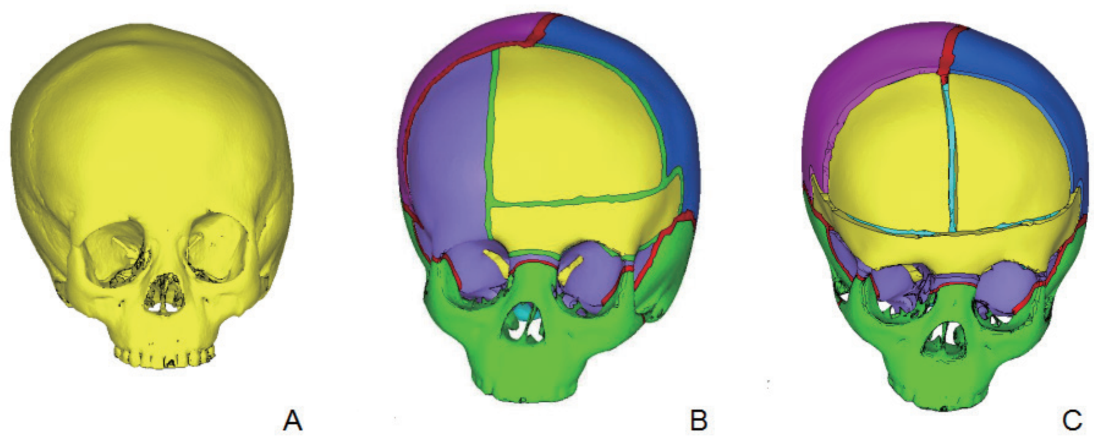

Fig. 1 The establishment of computer assisted design model using the Mimics software. A: Three-dimensional cranial computer assisted designed model of a case with left coronal synostosis; B: The computer assisted designed model of unilateral fronto-orbital advancement; C: The computer assisted designed model of bilateral fronto-orbital advancement.

Table 1: Parameters of the finite element model of a unicoronal craniosynostosis patient

Tissue	Material type	elasticity modulus (MPa)	Poisson ratio
Skull complex	elasticity	3690	0.22
Cortical bone	elasticity	9870	0.25
Bone suture	elasticity	1100	0.22
Scalp	elasticity	16.7	0.42

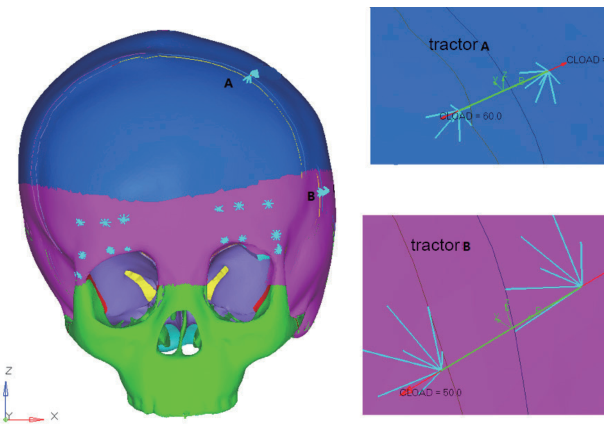

Fig. 2 Traction load on a FEM of unilateral fronto-orbital advancement: Simulating the traction at point A, near the midpoint of frontal osteotomy line in the forehead, and taking the simulation of traction at point B, near the midpoint of temporal osteotomy line of the frontal bridge. CLOAD and the number in the figure represent force loading.

Parameter settings for model materials

Owing to the limited number of pediatric cadavers available, the cranial parameters of the finite element of the child's head in this study referred to the skull elastic modulus and the suture of the 71 skull samples tested by Davis [5] et al in 2012. The specific material assignment parameter settings was shown in Table 1. We set the average thickness of skin and soft tissue according to the reconstructive results of CT, which was defined as shell material.

Boundaries and loads

The stress to the skull 3D FEM of craniosynostosis was loaded. The intracranial pressure of the skull cavity is uniformly applied with 2kpa. The center of the occipital macropore was constrained as boundary condition. The loads and boundaries applied to the FEMs of unilateral and bilateral fronto-orbital advancement were the same as above. Traction loading was performed on the unilateral fronto-orbital advancement FEM afterward (Fig. 2). From the experience of Wang Q et al and Jeong WS et al[6,7], as well as the experience of our team, point A and point B in the forehead and tempus area were selected for traction loading respectively. Three working conditions were then established. (1): 50 Newton (N) of traction force was applied at point A and 50N at point B with 2Kpa of intracranial pressure. (2): 80N of traction force at point A and 50N at point B with 2Kpa of intracranial pressure. (3): 100N of traction force at point A and 50N at point B with 2Kpa of intracranial pressure.

The definition of the three-dimensional planes were set before data analysis. The plane passing through the center of the sella turcica which parallelled to the Frankfort plane was the horizontal plane. The sagittal plane was the plane perpendicular to the horizontal plane through the midpoint of the sella turcica and the posterior margin of the occipital foramen. Passing through the midpoint of the sella turcica and perpendicular to both the horizontal and sagittal planes was the coronal plane. Supraorbital notch point, midpoint of supraorbital margin, frontal temporal point and frontal zygomatic suture point were selected as the bony landmarks. The absolute value of X was defined as the distance of the marker point from the sagittal plane. The absolute value of Y was defined as the distance of the marker point from the horizontal plane. The absolute value of Z was defined as the distance from the landmark point from the coronal plane. When the internal volume of the cranial cavity was above the normal volume (1550ml) and the deviation of the bilateral landmark points was 10% (the ratio of the difference between the affected side and the healthy side to the healthy side value), the results was the most effectve.

Finally, the grid file was input into ABAQUS 6.13(America, ABAQUS Inc.) for post-calculation processing and the opital traction loads was obtained.

RESULTS

In this study, a FEM of a 4-node first-order tetrahedral element was established by DICOM data of a three-dimensional skull CT of a male patient, including a skull model, a unilateral and a bilateral fronto-orbital advancement model (Fig. 3).

Through the stress distribution diagram of the skull FEM(Fig. 4), it can be seen that there were a few stressincreasing areas in the left frontal bone, the left temporal bone and the left parietal bone. And the stress distribution of the middle cranial fossa is relatively concentrated in the stress distribution map of the skull base. The FEM stress distribution analysis of the fronto-orbital anterior osteotomy simulation (Fig. 5) showed that the stress around the frontal and bilateral fronto-orbital osteotomy lines increased. The stress of anterior cranial fossa, especially closed to the affected side, decreased after the unilateral front-orbital advancement was simulated.

Deformation analysis was carried out when stress of 50N, 80N, 100N were applied to the traction point A and 50N traction force was applied to the B point. The results of the X value, Y value and Z value deviation rate of every condition are respectively shown in Table 2, Table 3, and Table 4.

The above results show that the application of traction can make the bone flap move inward, downward and forward. Considering the treatment principle of overcorrection and the limit of traction, it is considered that the best traction of this model is 80 N at point A and 50N at point B by preliminary assessment. The deformation diagram is shown in Fig.6.

DISCUSSION

For the field of craniofacial surgery, computed tomography is the most commonly used source of FEM data. High-resolution CT can preserve the details of tissue, especially bone tissue, which can reduce error during modeling and obtain a higher geometrically similar three-dimensional FEM. Finite element analysis has been successfully used to analyze the changes in biological stress of human

Table 2 Deviation results of X values of bony landmarks of a unicoronal craniosynostosis patient (%)

Landmark	X value diviation rate (in the left-right direction)			
	Before distraction	Traction (point A 50N, point B 50N)	Traction (point A 80N, point B 50N)	Traction (point A 100N, point B 50N)
Supraorbital notch point	-18.2%	-28.6%	-29.4%	-29.9%
midpoint of supraorbital margin	-12.2%	-20.0%	-20.5%	-20.9%
frontal temporal point	-2.8%	-8.2%	-8.6%	-8.8%
frontal zygomatic suture point	-3.8%	-8.9%	-9.3%	-9.5%

Table 3 Deviation results of the Y value of the bony landmark of a unicoronal craniosynostosis patient (%)

Landmark	Y value diviation rate (in the up and down direction)			
	Before distraction	Traction (point A 50N, point B 50N)	Traction (point A 80N, point B 50N)	Traction (point A 100N, point B 50N)
Supraorbital notch point	31.7%	22.2%	20.9%	20.0%
midpoint of supraorbital margin	42.3%	32.7%	31.5%	30.6%
frontal temporal point	84.2%	74.1%	73.0%	72.3%
frontal zygomatic suture point	603.1%	545.8%	539.4%	535.2%

Table 4 Deviation results of the Z value of the bony landmark of a unicoronal craniosynostosis patient (%)

Landmark	Z value diviation rate (in the anteroposterior direction)			
	Before distraction	Traction (point A 50N, point B 50N)	Traction (point A 80N, point B 50N)	Traction (point A 80N, point B 50N)
Supraorbital notch point	-6.3%	3.7%	4.4%	4.8%
midpoint of supraorbital margin	-9.2%	1.2%	1.9%	2.4%
frontal temporal point	-13.1%	-0.8%	0.1%	0.6%
frontal zygomatic suture point	-2.9%	10.8%	11.8%	12.4%

bones under physiological or external forces, helping people to better understand biomechanical properties and changes, which has been widely used in various fields such as automobile manufacturing industry and medicine [8,9]. For the treatment of craniosynostosis, finite element analysis has also begun to be studied [10, 11]. In this study, a FEM of unicoronal synostosis, two FEMs of unilateral and bilateral fronto-orbital advancement were

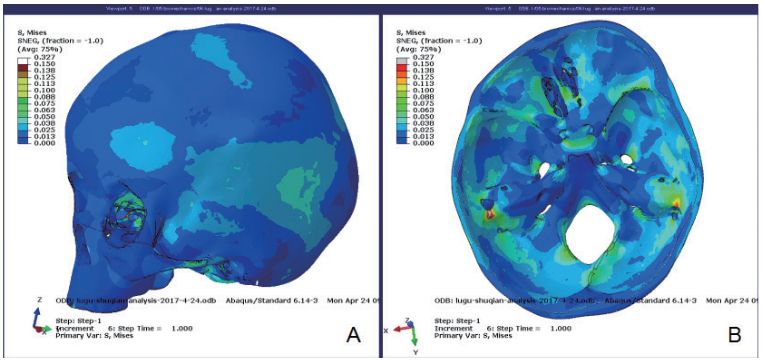

Fig. 3 Grid partitioning and preprocessing of finite element model of unilateral coronal synostosis. A: Finite element model of premature closure of cranial suture; B:FEM of unilateral fronto-orbital advancement simulation; C Finite element model of a bilateral fronto-orbital simulation advancement simulation.

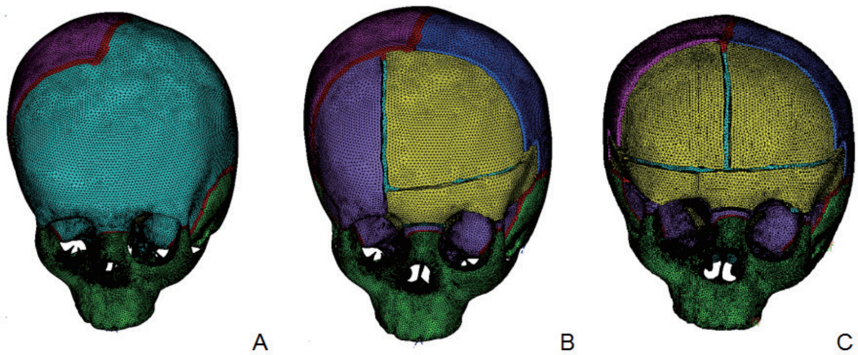

Fig. 4 Stress distribution map of finite element model of unilateral coronal synostosis A: Stress distribution showed in the left frontal, temporal and parietal bone areas, the cranial sutures of this model had greater stress; B: The skull base analysis showed the left anterior and middle cranial fossae had larger stress than right, especially in the anterior cranial fossa. In the illustration, blue represented decreased stress, and green represented increased stress.

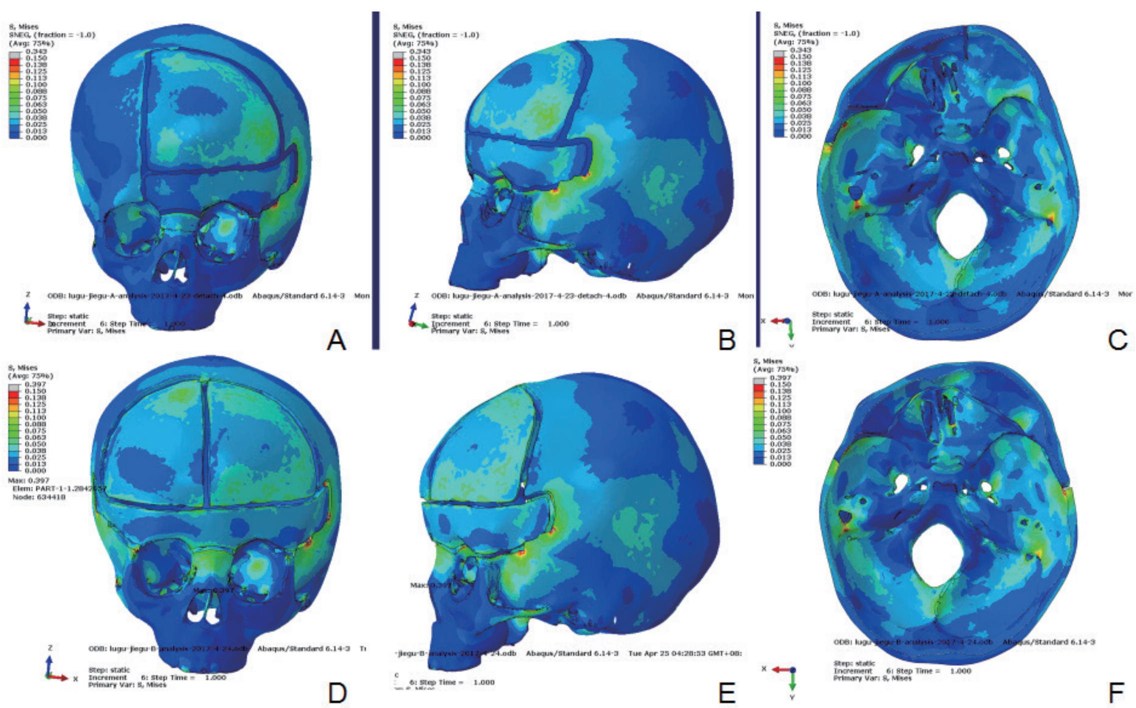

Fig. 5 Stress distribution map of FEM of unilateral fronto-orbital osteotomy: A: Frontal view showed increased stress around the osteotomy line; B: Lateral view showed stress concentration around the osteotomy line; C: The skull base view showed decreased stress in anterior cranial fossa. Stress distribution map of FEM of bilateral frontal-orbital advancement: D: Frontal view showed stress concentration around the osteotomy line; E: Lateral view showed stress concentration; F: The skull base view showed decreased anterior fossa stress.

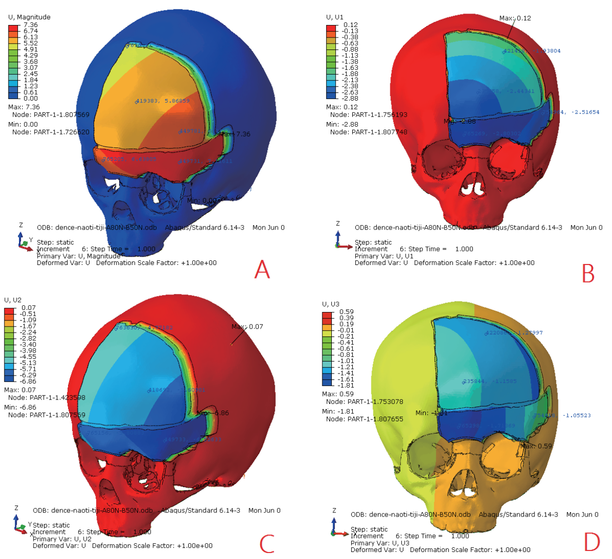

Fig. 6 The deformation diagram of the traction force of 80 Newton at point A, 50 Newton at point B. A: The comprehensive deformation map of the skull model; B: The deformation diagram of the skull in the left and right directions demonstrated the stress was larger at peripheral, resulting in the bone flap interiorly moving; C: The anteroposterior cranial deformation diagram showed larger inner stress, resulting in the bone flap tended to move forward; D: the superoinferior deformation map demonstrated the stress was larger in the interior.

established based on three-dimensional cranial CT. The pathophysiological mechanism of craniosynostosis can be explored. Personalized FEM analysis, disease outcome prediction, optimal surgical plan, and micro-internal tractor can be designed using biomechanical characteristics.

Although finite element simulation has been widely used in adult head impact test research, it is very difficult to experimentally measure the elastic modulus of biological specimens of specific age because of the difficulty in obtaining the skull of the child. Lapeer and Prager[12] literaturely reported the establishment of a baby skull model to analyze head deformation during childbirth . Klinich [13] et al. established a three-dimensional skull model of a 6-month-old child for experimental study of head impact. Coats [14] et al. established a 1.5-month-old baby FEM to study the mechanical characteristics of brain soft tissue when the head was impacted. The above studies have some limitations that they did not divide the detailed structures of the cortical bone and the diploe. Davis [5] et al. measured the mechanical parameters of the head specimen of a 6-year-old child and found that the elastic modulus of the cortical bone of the 6-year-old child was 9.87 Gpa, and the elastic modulus of the skull complex (the inner and outer cortical bone of the skull and the diploe) was 3.69 Gpa, the elastic modulus of the skull joint was 1.1Gpa. The patient's age of our study was about 6 years old, and the data reported by Davis and others was applied to make the simulation process as realistic as possible.

The results of this study showed that the premature closure of cranial suture leaded to an increase in the biological stress of the affected skull. Under the same intracranial pressure, the affected side has a larger change in the shape of the skull than the healthy side, thus the typical symptom of the anterior oblique head deformity and the flattening of the affected side occurred. When the long-term state existed, the thickness of the affected side of the skull plate gradually decreased. It was consistent with the symptoms of common clinical finger pressure sigh and thinning of the skull, and there were certain changes in the biomechanics of the skull base. The increase of biological stress may be related to the asymmetry of the skull base, which was basically consistent with the results of the previous skull base morphology measurement [15]. It was also a side proof that the FEM had certain authenticity. In addition, the bone flaps in areas with high stress may be thinner, and there may be a possibility of tearing and slipping when fixing the nails.

We have established a unilateral and bilateral fronto-orbital advancement simulation FEM. This FEM can be used to show that the fronto-orbital osteotomy can reduce the high stress state of skulls, and also relieve the skull base, especially the anterior cranial fossa. Besides, the FEM suggested that stress concentration areas appear around the osteotomy line, especially near the tenon. Considering the right angle structure of the tenon, the smooth osteotomy line can reduce the surrounding stress.

Hirabayashi [16] firstly reported the use of internal distractors for the treatment of premature closure of coronal sutures on the basis of the traditional fronto-orbital anterior osteotomy. In traditional surgery, the advantage of the distractor is that it can reduce injuries, avoid the formation of the surgical dead space, reduce the risks of postoperative complications and continuously form new bone on the osteotomy line during the traction process and avoid bone defects. The cranial cavity can be expanded well.

In this study, a FEM database of craniosynostosis was established which can classify the degree of malformation, predict disease development, assist surgical treatment and guide the design of internal distractor. More cases are needed to expand our database and help modify our surgical strategies.

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Ethical Approval: This study was conducted in accordance with the Helsinki Declaration.

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