Surgical Treatment of Craniosynostosis based on a Statistical 3D-Shape Model: First Clinical Application

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Abstract. Surgical intervention in cases of craniosynostosis often lacks objective criteria for the reshaping process of the skull. The application of a statistical 3D-shape model of the upper skull may provide an objective, yet patient-specific guidance for the remodelling. To this end, a statistical 3D-shape model of the upper skull is generated from a set of 21 MRI data sets of healthy infants. Usually, no pre-operative MRI scan is available for the infant patients, hence the matching of the model towards the pathological skull of the patient is performed on the basis of anthropometric distances. Results from the first clinical use of the proposed technique are presented.

Keywords: craniosynostosis, skull, surgery planning, statistical 3D-shape model, correspondence problem

1. Introduction

Premature ossified cranial sutures of infants (craniosynostis) often lead to skull deformities in the growth process. This can lead to increased intracranial pressure, vision, hearing, and breathing problems. Since research on the correction of underlying disorders on the cellular level is still being carried on patients with craniosynostosis depend on surgical intervention for preventing or reducing functional impairment and improving their appearance.

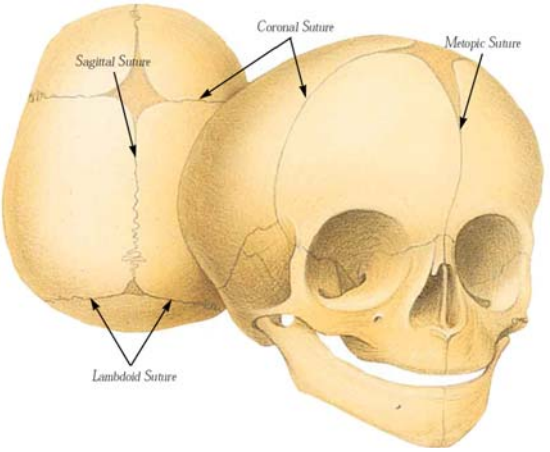

Fig. 1: Cranial sutures of infant skull (image courtesy of www.craniofacialcenter.com)

The most commonly used surgical procedure consists of bone fragmentation, deformation (reshaping) and repositioning based on standards developed by Paul Tessier [1] and refined by Daniel Marchac and Dominique Renier [2]. A major problem is the evaluation of the aesthetic results of reshaping the cranial vault in small children as the literature does not provide sufficient criteria for assessing skull shape during infancy. A definition of the correct target shape after surgery is missing. The most important and in many cases only indication of the best possible approximation of the skull shape to the unknown healthy shape is left to the subjective aesthetic assessment of the surgeon. This prevents impartial control of therapeutic success and aggravates guidance and instruction of the remodelling process for inexperienced surgeons.

Statistical models of shapes offer the possibility for automated reconstruction of unknown shapes, as has been shown in numerous applications [3]. The goal of this work is to develop a method for patient-specific preoperative planning of skull reshaping based on such a statistical 3D-skull model.

2. Material and Methods

In order to establish objective criteria for the reshaping process, we propose to perform statistical analysis of normally developed cranial shapes [4]. The idea is to compute an average shape and the most characteristic variations from a training set of skulls. Pathological shapes are then projected onto the space spanned by the healthy shapes. The resulting shape will provide a patient-specific proposal for the remodelling process.

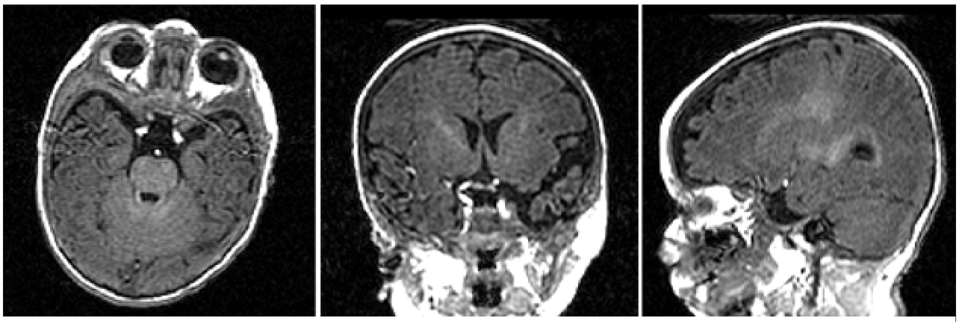

Fig. 1: MRI data of normally developed skulls

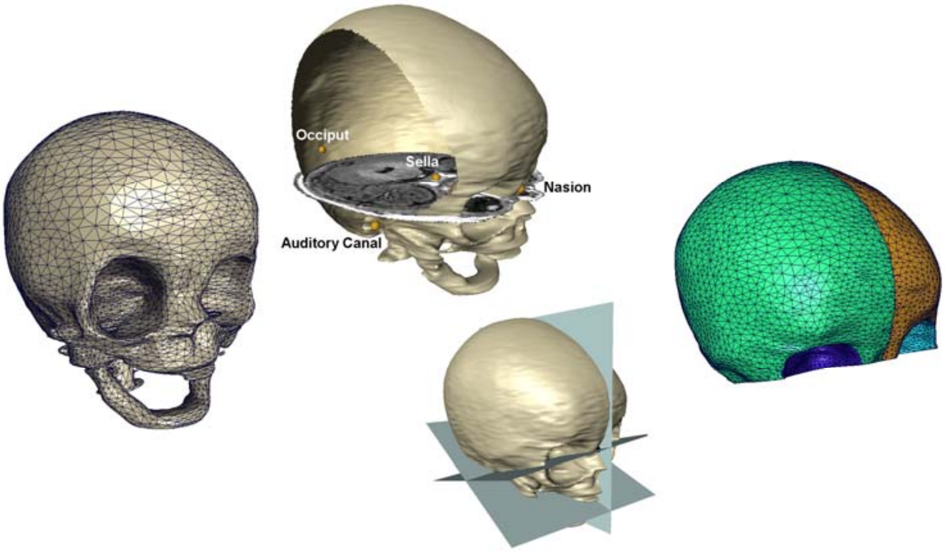

Fig. 2: Surface reconstruction of neurocraniums of infants for statistical shape modelling. Left: reconstruction of the bone surface from the interactive segmentation. Middle: landmarks (top) determining cutting planes (bottom). Right: final skull patches used in the statistical analysis.

2.1 Acquisition and Preparation of the Training Set

The samples for the statistical analysis are generated on the basis of MRI data of normally developed skulls (Fig. 1), which are segmented interactively by an anatomical expert. From these segmentations polygonal surfaces are reconstructed. A typical result is shown in Fig. 2, left. Next, the relevant region for the surgical intervention is determined. Therefore, four landmarks are defined on the reconstructed skull surfaces (Fig. 2, middle-top):

(1) meatus acusticus externus: the entries to the auditory canals.
(2) nasion: foremost point of the sutura naso-frontalis in the mid-sagittal plane.
(3) sella: center of the sella turcica (hypophysis)
(4) occiput: palpable elevation of the os occipitale in the mid-sagittal plane.

These landmarks define a set of planes through which the surface mesh is cut (Fig.2, middle-bottom). The resulting surface of the affected neurocranial region serves as input for the statistical analysis and consists of four sub-regions (Fig.2, right): right and left orbital regions, left and right upper skull region.

2.2 Statistical 3D-Skull Model

The main challenge in performing statistical 3D-shape analysis lies in the identification of anatomically corresponding points on skulls of different patients (correspondence problem, inter-subject matching [5]). In this work, the statistical 3D-shape model is generated using the method of consistent patch decomposition and parameterization. Corresponding points on each training surface are defined by mapping anatomically corresponding regions from one shape to another by minimizing metric distortion of the patches. The regions were defined in the previous section (see Fig. 2, right). For details of this procedure, refer to [6]. This allows for the representation of all training shapes in common vector space and subsequent statistical analysis via principal component analysis (PCA) [7]. The goal of this analysis is to represent as much variance contained in the training set by as few parameters as possible. These essential degrees of freedom of the resulting statistical model enable us to explore characteristic cranial shapes within a normal variation, and to reconstruct new shape occurrences by linear interpolation of all or just a few selected eigenmodes (i.e. major modes of variation).

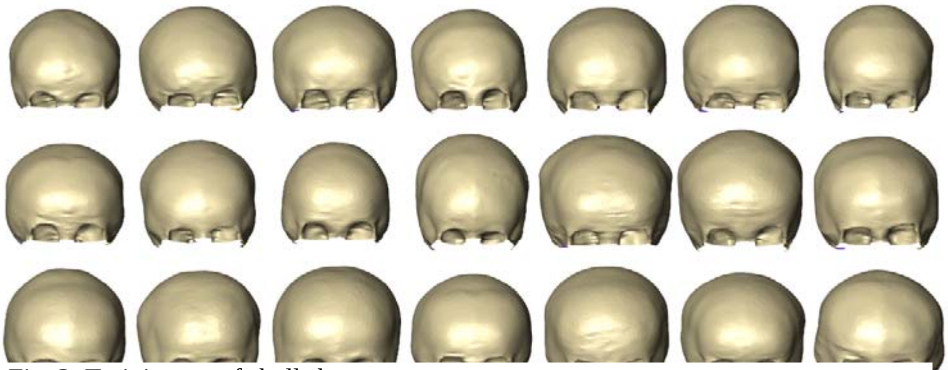

Fig. 3: Training set of skull shapes.

2.3 Template Shape Generation for Surgical Remodelling

The 3D cranial model serves as a template for the reshaping process, by finding an optimal fit of any of its variations to a given malformed skull [8]. Usually, no pre-operative MRI scan is available for the infant patients (mostly under the age of one year) in order to avoid unnecessary anaesthesia. Hence the matching of the model towards the pathological skull of the patient is performed by non-invasively measuring anthropometric distances that are not affected by the surgical intervention:

(1) width between both entries of the auditory canals
(2) distance from nasion to occiput
(3) height between vertex and the midpoint of the line between the auditory canals

These distances are extrapolated to the skull surface by approximating the skin and skull thickness. The shape model instance that best fits these measurements is selected as a template for the reconstruction process. The resulting shape instance represents an individual interpolation of all shapes contained in the training set.

3. Results

3.1 Statistical Skull Model

A statistical shape model was created from 21 MRI data sets (patient age: 3 to 10 months). The completeness of the model was tested in a leave-one-out experiment (cf. [6]) on all 21 data sets available: on average the model is capable of approximating any other arbitrary skull shape with an error of 0.7 +/- 0.2 mm (mean symmetric surface distance).

3.2 First Clinical Application

In a first clinical application, the statistical model was pre-operatively matched to a patient using the method described in section 2.3. From this computed shape model instance a life-size facsimile of the skull was built and taken to the operating room to guide the reshaping process. Figures 4-8 illustrate the surgical procedure and the role of the statistical skull model (photos taken by F. Hafner):

(Fig. 4) Three different views of a patient with trigonocephaly (ossification of the suture running down the midline of the forehead) - before surgery.

(Fig. 5) Cutting lines indicated on the skull, removed frontal skull region before the reshaping, facsimile of shape model instance on which bone parts are reshaped.

(Fig. 6) Bone stripe before and after reshaping, result of reshaping process on model.

(Fig. 7) Microplates for fixating bone pieces on remaining skull are also shaped on the model, result after fixation of reshaped bone on skull.

(Fig. 8) Comparison between pre- and post-operative situation (from left to right): patient 2 months before surgery, immediately before surgery, fac-simile of the target shape derived from the statistical model, patient immediately after surgery, 3 weeks after surgery.

4. Conclusions

The application of a statistical shape model as a tool for guiding the skull reshaping process in cases of craniosynostosis has proven successful, as shown in a first clinical evaluation (Fig. 4). Statistical shape models are capable of providing objective, yet patient-specific criteria for the reshaping process. At the same time they accelerate the process of reshaping as they prevent mistakes or uncertainties followed by time consuming corrections.

We want to extend the number of samples in the training set to improve the completeness of the statistical shape model. It will be examined whether the model can be applied for segmentation purposes [9] as well, as this is the most time-consuming task in the model generation pipeline.

In this work, the matching of the model was carried out on the basis of a few landmark measurements. In the future we want to explore the possibilities of 3D surface scanners to acquire pre-operative patient data as well as post-operative data for long-term validation.

References

[1] P. Tessier: Total facial osteotomy. Crouzon's syndrome, Apert's syndrome: oxycephaly, scaphocephaly, turricephaly. Ann Chir Plast. 1967, 12(4): 273-286.

[2] D. Renier, E. Lajeunie, E. Arnaud, D. Marchac: Management of craniosynostoses, Childs Nerv Syst, 2000, Nov 16(10-11), pp. 645-658.
[3] H. Lamecker, S. Zachow, H. Haberl, M. Stiller: Medical Applications for Statistical 3D-Shape Models, Fortschritt-Berichte VDI (S. Weber et al., eds.), 17 (258), Computer Aided Surgery around the Head, p. 61, 2005.
[4] H. Lamecker, M. Zöckler, H. Haberl, S. Zachow, H.-C. Hege: Statistical Shape Modeling for Craniosynostosis Planning, in Proc. Advanced Digital Technology in Head and Neck Reconstruction, Banff, 2005.
[5] J. Hajnal, D. Hill, D. Hawkes: Medical image registration, CRC Press, 2001.
[6] H. Lamecker, T. Lange, M. Seebaß: Segmentation of the Liver using a 3D Statistical Shape Model, Technical Report, ZIB PaperWeb 04-09, 2004.
[7] T. Cootes, A. Hill, C. Taylor, J. Haslam: The Use of Active Shape Models for Locating Structures in Medical Images, Image and Vision Computing, 12 (6), pp. 355-366, 1994.
[8] S. Zachow, H. Lamecker, B. Elsholtz, M. Stiller: Reconstruction of Mandibular Dysplasia using a Statistical 3D-Shape Model, in Proc. CARS (H. Lemke et al, eds.), Int. Congress Series (1281), Elsevier, 2005, pp. 1238-1243.
[9] G. Székely, G. Gerig: Model-based segmentation of radiological images, Künstliche Intelligenz, 14 (3), pp. 18-23, 2000.

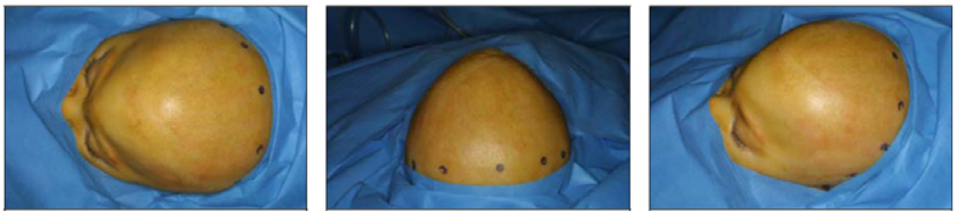

Fig. 4

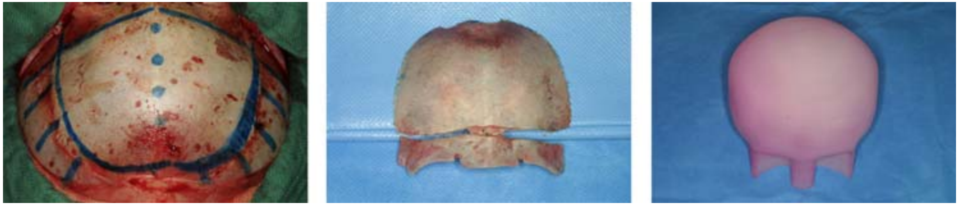

Fig. 5

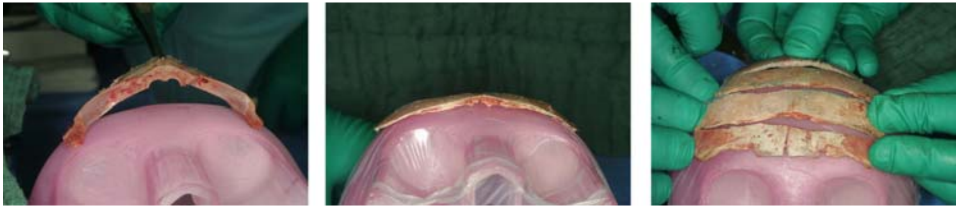

Fig. 6

Fig. 7

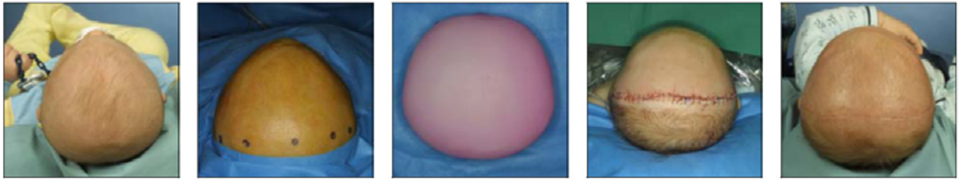

Fig. 8