Automated Classification of Skull Deformity in 3D Head CT Images using Regional Shape Information

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***Abstract*—We propose regional shape indices representing the degree of skull deformity for automatic classification and quantitative analysis of the skull deformities with sagittal and bicoronal synostosis on 3D head CT images. Regional shape indices are calculated by considering the degree of regional deformation of the deformed skull relative to the normal skull in each 3D bone segment separated by the sutures. In experimental results, the overall accuracy using multi-class support vector machine and random forest classifiers were estimated as 94.44% and 93.06%, respectively. our proposed regional shape indices can be used for early diagnosis and quantitative analysis of skull deformity with sagittal and bicoronal synostoses.**

Keywords— skull deformity; craniosynostosis; classification; quantification; regional shape feature

I. Introduction (*Heading 1*)

Craniosynostosis is one of the most common causes of skull deformities in infants and a condition in which one or more cranial sutures prematurely fused. This results in abnormal morphology as well as limited brain growth and intracranial hypertension [1]. Three-dimensional head computed tomography (CT) is the most standard imaging for early diagnosis of craniosynostosis and is an essential imaging for its surgical planning and postsurgical assessment. Although the 3D head CT images show excellent views of both the affected sutures and the overall head shape, determination of skull deformity is still prone to interobserver variability depending on clinical experience.

The traditional cranial index (TCI) used in clinical practice is calculated as the ratio of the maximum width of the skull to its maximum length from the projection image of the top view of the 3D CT image [2]. However, by measuring the shape of the skull seen from the top, the TCI can provide inaccurate information that does not take into account the shape of the entire skull. Thus, automatic classification and reliable quantification of the skull deformity is necessary.

In this paper, we propose regional shape indices representing the degree of skull deformity for automatic classification and quantitative analysis of the skull deformities with sagittal and bicoronal synostosis on 3D head CT images. Regional shape indices are calculated by considering the degree of regional deformation of the deformed skull relative to the normal skull in each 3D bone segment separated by the sutures. In experiments, our method show promising results in improved accuracy with the help of proposed indices, compared to the traditional cranial index.

II. Proposed Methods

A. Mean Normal Skull Model Construction and Deformation

To describe the regional deformation of the deformed skull relative to the normal skull, it is necessary to generate a mean normal skull model and match the mean normal skull model with the deformed skull through three-stage registration.

First, to construct a mean normal skull model, skull segmentation is required as a preprocessing step. A skull is segmented semi-automatically into a closed form without open suture and the segmented skull is modeled by surface using marching cubes algorithm. After then, to reflect the age-related difference in skull shape, three mean normal models of 3-6months, 7-12months, 13-24months are generated from the segmented normal skulls. Each mean normal model is decomposed into five cranial bone segments based on the sutures.

Second, the mean normal skull model is deformed to the deformity skull model using a three-stage registration. To align the mean normal model and the deformity skull model, a landmark-based registration is performed using relatively stable landmarks without deformation on the skull base. The five landmarks selected by the clinician consist of nasion, basion, opisthion and two porions. To adjust the alignment of the cranial surface, alternate surface-based and landmark-based registrations are performed repeatedly. Finally, multi-scale deformable registration is performed by using cubic B-spline-based non-rigid registration. The result of the deformable registration shows the movement of each surface point with different directions and distances defined by the local displacement vector.

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To calculate the regional shape indices, the local distance is calculated as a local displacement vector between the deformed mean normal skull model and the deformity skull model, and the sign of the local distance is determined based on the information of the inside and outside positions of the deformity skull model.

B. Shape Feature Extraction

To consider the regional shape difference of the deformed skull relative to the normal skull, we propose five shape indices including positive and negative regional distance indices and nearly zero, positive and negative regional area ratio indices in each bone segment separated by the sutures.

The positive and negative regional distance indices represent the expansion and reduction between the mean normal skull model and the deformity skull model and are calculated as the average value of positive and negative distances in each bone segment, respectively. The nearly zero, positive and negative regional area ratio indices represent the distribution of areas of small deformation, expansion and reduction between the mean normal skull model and the deformity skull model, which are calculated as the number of points with small, positive and negative distances versus the number of total regional bone points. The small deformation is defined experimentally to be less than 1mm.

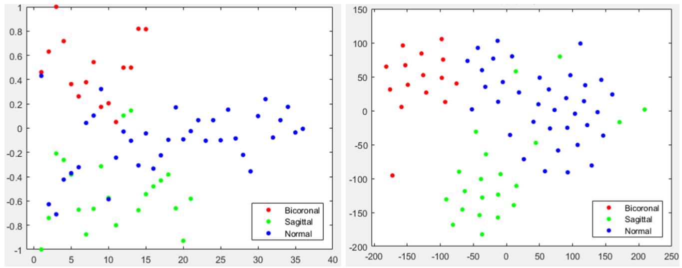
C. Shape Feature Classification

To analyze the proposed indices for differentiating deformity subjects with sagittal and bicoronal synostosis from normal subjects, we utilize the multi-class support vector machine (SVM) classifier and random forest (RF) classifier. A kernel with the radial basis function (RBF) was used in SVM, and multiple random decision trees (RDT) were bagged to avoid overfitting in RF.

III. Results

We evaluated our method on 36 normal subjects, 21 deformity subjects with sagittal synostosis, and 15 deformity subjects with bicoronal synostosis. The mean age of normal subjects was 9.22 months and ranged from 3 months to 22 months. The mean age of deformity subjects was 11.47 months and ranged from 2 days to 36 months. For normal and deformity subjects, CT data were acquired with three different high-speed multidetector systems. Each image had a matrix size of 512x512 pixels with in-plane resolutions of 0.25-0.46mm, and the slice thickness of 0.63-1.25mm. The number of images per scan ranged from 91 to 313. We compared the results of the classification with the TCI and proposed regional shape indices (RS), and validated datasets using leave-one-out cross validation method. To evaluate classification performance, accuracy, sensitivity, and specificity were calculated by comparing predicted results with the ground-truth.

Fig. 1 shows the feature visualization results, in which the various features were projected into 2D subspace by tSNE method. TCI showed severely low inter-class separability and widely scattered intra-class density, while regional shape indices were improve both the inter-class separability and intra-class density.



(a) (b)

Fig. 1. Results of tSNE feature visualization of (a) Traditional cranial index and (b) Regional shape indices

Table 1 shows the performance evaluation of the classification with the TCI and proposed regional shape indices using SVM and RF classifier. In classification with TCI, the sensitivities of sagittal and bicoronal synostosis and the specificity of normal were relatively low compared to those in the classification results of the proposed regional shape indices. Especially, the accuracy using RF classifier was significantly low. In classification with regional shape indices, the overall accuracy using SVM and RF classifiers were improved by 16.66% and 33.33% compared with classification using TCI, respectively.

IV. Conclusion

We proposed regional shape indices to quantify the skull deformity and classify the skull deformities with sagittal and bicoronal synostoses from normal subjects on 3D head CT images using proposed indices. In experimental results, the overall accuracy using SVM and RF classifiers were estimated as 94.44% and 93.06%, respectively. our proposed regional shape indices was efficiently distinguished from deformity and normal subjects and can be used for early diagnosis and quantitative analysis of skull deformity with sagittal and bicoronal synostoses.

TABLE I. Performance Evaluation of Classification Using TCI and Reegional Shape Indicies. The highest values were denoted (%)

		TCI		RS	
		SVM	**RF**	**SVM**	**RF**
Sagittal	Accuracy	84.72	72.22	**94.44**	**94.44**
	Sensitivity	66.67	61.90	**85.71**	80.95
	Specificity	92.16	76.47	98.04	**100.0**
Bi-coronal	Accuracy	93.06	87.50	**100.0**	97.22
	Sensitivity	73.33	66.67	**100.0**	**100.0**
	Specificity	98.25	92.98	**100.0**	96.49
Normal	Accuracy	77.78	62.50	94.44	**97.22**
	Sensitivity	86.11	58.33	97.22	**100.0**
	Specificity	69.44	66.67	91.67	**94.44**

The highest values were denoted in bold.

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