Computer-Aided Treatment Decision on Scoliosis Based on Three-Dimensional Radiographic Features

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***Abstract*—The purpose of this study is to develop a computer-aided decision making system for scoliosis treatment based on biplanar spinal radiographs. Three-dimensional (3D) features were automatically extracted from the 3D spinal model that was reconstructed by using the self-calibration algorithm from landmarks identified by users on radiographs. The *k*-nearest-neighbor model was trained and then was used to determine the treatment for a scoliotic curve as observation, bracing, or surgery. With leave-one-out methodology, 31 cases were used to test the system performance. Experimental results showed that the system could achieve accuracy of 91.9% and consistency of 96.8%. This system can be an objective aid to surgeons in the task of treatment decision for scoliosis.**

***Index Terms*—idiopathic scoliosis, treatment decision, radiograph, three-dimensional feature**

I. Introduction

Idiopathic scoliosis is a disorder that generates a complex three-dimensional (3D) deformation of the spine with unknown cause [1]. It affects about 2–4% of the adolescent population [2]. About 2.2% of these adolescents will require treatment, consisting of observation, orthotic (brace) treatment, or surgery [3]. Treatment decisions are mainly based on consideration of the patient's physiologic maturity, curve severity, and the chances of progression. Currently, X-ray is the most commonly used imaging modality for assessing scoliosis due to its acceptable radiation dose, low costs, and flexibility of being able to image the whole spine in different poses. The Cobb angle method is the gold standard [1] for the evaluation of spinal curves on a coronal radiograph. A Cobb angle less than 10° is not considered to be scoliosis. Spinal deformity with a Cobb angle of 10° to 25° will be monitored regularly until skeletal maturity or significant curve progression. If the Cobb angle is 25° to 45°, brace treatment is suggested. If the Cobb angle is greater than 45°, surgery is usually recommended [3]. Although the Cobb angle is the most widely used method, it is a two-dimensional (2D) measurement providing only a simplification of the real 3D spinal deformity. Carpineta *et al.* [4] demonstrated that the Cobb angle measured on a coronal radiograph did not indicate whether the plane of maximum deformity lay behind the coronal plane or in front of it.

Because of the 3D nature of scoliosis, treatment decisions should be made based on 3D features. During the past 30 years, numerous methods have been developed to represent the spine in three dimensions and to perform 3D measurements from biplanar radiographs. Lin [5] calculated the total curvature values of 17 vertebrae from a simplified 3D spine model and developed an artificial neural network based on the curvature values for automatic King classification. Poncet *et al.* [6] extracted the geometric torsion and evaluated the relevance of geometric torsion as a 3D index of scoliosis. Duong et al. [7] used a wavelet transform of the vertebrae centroids and a fuzzy clustering algorithm to group 3D spine shapes. Although this method is technically elegant and illustrates that 3D classifications are important, it is not considered to be very intuitive by physicians. Sangole et al. [8] calculated four indices of the thoracic segment within Lenke Type 1 curves and proposed a new means to report 3D spinal deformities bases on planes of maximal curvature. Kadoury et al. [9] analyzed five features of Lenke Type 1 curves by a non-linear manifold imbedding algorithm. They demonstrated the existence of an additional hyper-kyphotic subgroup in Lenke Type 1 curves and concluded that the complex space of spine variability could be modeled by a low-dimensional manifold. Our previous study [10] showed that 3D geometric torsion revealed structural differences that were not apparent in the Cobb measurement.

The purpose of this study is to develop a computerized decision making system based on 3D features for a more objective decision of scoliosis treatment and to evaluate its performance. The developed system consisted of three steps, that is, the 3D spine reconstruction, the feature extraction, and the decision making. Accuracy and repeatability of this system were evaluated.

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II. Materials and Methods

Thirty-one idiopathic scoliotic patients (27 girls and four boys) were selected in this study. These cases were consistently determined by five experts as treatment of observation for nine cases, bracing for 21 cases, and surgery for one case. The average age at the time of the visit was 14 ± 2 years. Patients with a previous spinal surgery were excluded. For each patient one coronal and one sagittal radiograph were obtained. The main curves of patients included in this study presented a mean Cobb angle value of 39 ± 12° measured by an orthopedic surgeon on the coronal radiographs. An informed consent from all patients/parents was obtained along with the approval of the institutional review board.

The processing procedure of the developed system is described in the flowchart shown in Fig. 1. The details of the system are described in the following subsections.

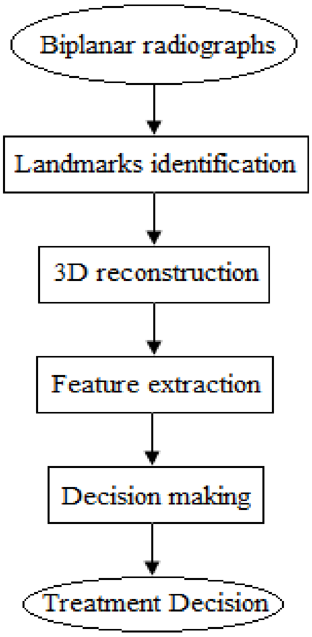
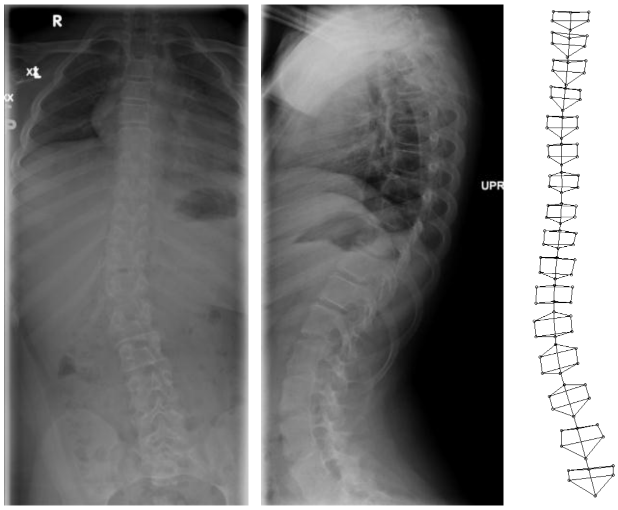


Figure 1. Processing procedure of the system.

A. Three-Dimensional Model Reconstruction

To obtain the 3D spine model, six anatomic landmarks per vertebra were manually identified and matched on biplanar radiographs. These landmarks were the centers of the superior and inferior endplates and the superior and inferior extremities of pedicles on each vertebra. For each subject, the 3D spine model was reconstruction from biplanar radiographs by using the self-calibration algorithm [11] that computed the geometrical parameters of the radiographic setup. The first step of the self-calibration method was to reconstruct the six landmarks per vertebra using the initial approximation of the geometrical parameters. The 3D landmarks were then retro-projected onto biplanar images using the projection matrices calculated from the geometrical parameters. The geometrical parameters were then updated by using the Levenberg-Marquardt algorithm [12] that minimized the mean squared distance between the projections of the landmarks of unknown 3D coordinates and those identified by the surgeon on the biplanar images. The set of parameters were therefore regenerated and were used for the reconstruction and projection again. This procedure was repeated until the system reached a steady state, where the landmark retro-projection error fell to a minimum. The optimized geometrical parameters were used to obtain the final 3D coordinates of matched landmarks. As an example, Fig. 2 shows the coronal and sagittal radiographs of a scoliotic spine and the reconstructed 3D spine model.



(a) (b) (c)

Figure 2. 3D reconstruction of the spine. (a) Coronal radiograph. (b) Sagittal radiograph. (c) Reconstructed spinal model.

B. Three-Dimensional Feature Extraction

Based on the reconstructed 3D landmarks, the 3D vertebral centroid was calculated as the mean of the four bases of pedicles. For each spinal shape, a mathematical parametric description was obtained by fitting a 3D curve through vertebral centroids using a least square Fourier series method. In the discrete space, this 3D curve of central axis was represented by a series of points. These points formed a series of connected vectors, as shown in Fig. 3. Eight geometric features of the spine were extracted from the 3D model represented by the 3D curve and landmarks.

Computerized cobb angle of the thoracic curve: this was an equivalent of the Cobb angle, which was computed from the coronal view of the 3D curve. Inflexion points of the curve projected on the coronal plane were identified, and the angle between two lines perpendicular to the curve at its inflexion points was calculated as the Cobb angle.

Computerized kyphosis: it was the Cobb angle computed from the sagittal view of the 3D curve constrained to T4 to T12.

Computerized lordosis: it was the Cobb angle computed from the sagittal view of the 3D curve constrained to L1 to L5.

Computerized cobb angles in the planes of maximum and minimum deformity: these two planes were determined by rotating the spine around the vertical axis with 1° increments until a maximum or minimum Cobb angle value of the thoracic curve was measured [13]. The Cobb angle in these two planes was recorded.

Orientation of the plane of maximum curvature: it was measured as the angle between the maximum plane and the coronal plane. That is, a plane of maximum curvature parallel to the coronal plane had an orientation value of 0 ° whereas a plane of maximum curvature parallel to the sagittal plane had an orientation value of 90 °. In a normal thoracic spine without scoliosis, since the curve was the kyphosis which lay in the sagittal plane, the orientation of the maximum curvature plane should be 90 °.

Maximum geometric torsion: the discrete form of geometric torsion T was calculated according to the definition proposed in [5]:

$$T_{123} = \frac{1}{K_{12} \cdot K_{23}} \frac{\sin \gamma_{123}}{S_{123}} \quad (1)$$

where K was the discrete form of curvature:

$$K_{12} = \frac{\sin \alpha_{12}}{S_{12}}, \quad K_{23} = \frac{\sin \alpha_{23}}{S_{23}}. \quad (2)$$

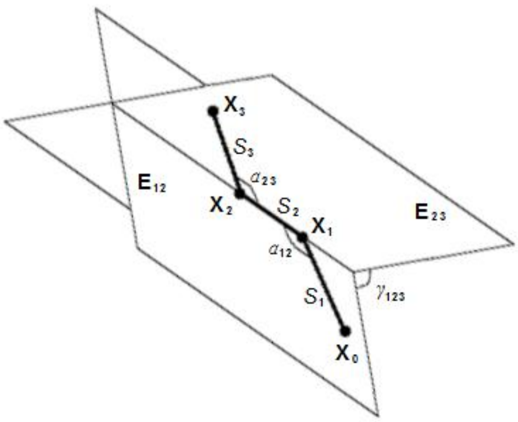


Figure 3. Geometrical representation of torsion.

As illustrated in Fig. 3, S_{12} is the average length of segments S_1 and S_2, and S_{123} is the average length of segments S_1, S_2, and S_3. The α_{12} denotes the angle of deformity between two vectors $\mathbf{e}_1$ and $\mathbf{e}_2$, where $\mathbf{e}_1 = (\mathbf{x}_1 - \mathbf{x}_0) / S_1$, and $\mathbf{e}_2 = (\mathbf{x}_2 - \mathbf{x}_1) / S_2$. The γ_{123} denotes the torsion angle between the two planes determined by the vectors:

$$\mathbf{E}_{12} = \mathbf{e}_1 \times \mathbf{e}_2, \ \mathbf{E}_{23} = \mathbf{e}_2 \times \mathbf{e}_3. \quad (3)$$

The torsion values calculated from the vertebral centers were compared to obtain the maximum torsion.

Orientation of Apical Vertebra: the apical vertebra of a curve was identified and its 3D orientation was then measured based on the coordinates of landmarks.

C. Computerized Treatment Decision

Based on the extracted features, treatment decision was determined for a scoliotic curve as observation, bracing, or surgery by using the *k*-nearest-neighbor model. For a case to be decided, the Mahalanobis distances between this case and the known examples (i.e., the training cases with known decisions) regarding eight features were calculated. The *k* examples with the smallest distances were selected as the nearest neighbors. The decision was determined by the majority vote of the *k* neighbors. Using leave-one-out methodology, the *k*-nearest-neighbor model was trained and tested.

III. Experiments and Results

In the experiments a pediatric orthopedic surgeon with 10 years of experience in scoliosis clinic and the software developer without clinical experience identified landmarks on biplanar radiographs, respectively. The computer automatically performed the tasks of reconstructing the 3D model, extracting eight features, and then making treatment decision. The value of *k* of the *k*-nearest-neighbor model was set as 3, 5, 7, and 9, respectively. The evaluation of the system was performed in two parts: accuracy and repeatability. To evaluate accuracy, the decisions made by the system under different *k* values were compared with those provided by five experts consistently. Results are presented in Table I. It was shown that with $k = 7$ the system obtained the average accuracy of 91.9%.

Under the two observers' identifications, the decisions were compared to assess the interobserver repeatability by using the kappa statistic [14]. Results are presented in Table II. The kappa value was in the range from 0.772 to 0.936. With $k = 7$ or 9, under two observers' identifications, the system made consistent decisions in 30 cases.

Two orthopedic residents also read these radiographs and made their decisions of treatment. The average accuracy of the two residents was 77.4% and consistency was 87.1% with kappa value of 0.768.

TABLE I. Accuracy of the System

k	Accuracy		
	Observer 1	Observer 2	Average
3	74.2%	74.2%	74.2%
5	80.6%	83.9%	82.3%
7	93.5%	90.3%	91.9%
9	87.1%	90.3%	88.7%

TABLE II. Repeatability of the System

k	Repeatability	
	Consistency (%)	Kappa value
3	87.1%	0.772
5	90.3%	0.820
7	96.8%	0.932
9	96.8%	0.936

IV. Discussions

Because of the 3D nature of scoliosis and observer-dependent interpretation of the 2D radiographs, the treatment decision for scoliosis based on 2D radiographs may be different among surgeons, especially for the marginal cases. We proposed a computerized method to provide objective treatment decision for scoliosis based on the 3D features extracted from radiographs. The system achieved accuracy of 91.9% and consistency of 96.8%. Comparing with the performance of two residents of 77.4% accuracy and 87.1% consistency, it indicates that the developed system has the potential to help residents with few experiences improve decision accuracy and consistency. It can provide a useful reference for surgeons, either by consistently extracting the 3D quantitative features or by uniformly determining treatment schemes. It can server as an alternative to double reading by surgeons. In clinical practice, the variability of the second human reader exists. Since the information provided by the computer is independent to human interpretations, it can be used as a second opinion that is immune to human variability.

One of the fundamental issues in the implementation of the computerized system was the determination of the quantitative features that would be appropriate and effective for characterizing scoliosis. In this study, eight features were extracted to describe scoliosis deformity. These features included the computerized Cobb angle which was similar to the traditional Cobb angle but was calculated from the 3D spinal model. In addition, the geometric torsion and vertebral 3D orientation that were true 3D measurements were used for the decision. Experimental result of 91.9% accuracy demonstrated the accuracy of the proposed system.

There were limitations to our study. Firstly, this system depended on the self-calibration algorithm to reconstruct the 3D spinal model, which was based on manual identification of landmarks. We need further investigate the relationship between the reliability of the reconstructed 3D model and the final computerized decision. Secondly, besides the features derived from radiographs, other features, such as the patient's age and curve type should be investigated to find out whether these features would be useful for improving the performance of the system. Finally, only 31 cases were used and there was only one experienced surgeon in the tests. This situation might cause bias in the evaluation. To confirm the effectiveness of the system as an aid tool to surgeons in treatment decision making, we would need more data to perform observer study, where the performance of surgeons with and without aid of this system would be evaluated. Ongoing work is underway to train a better performance system by collecting more extensive types of cases.

V. Conclusions

We developed a computer-aided system for treatment decision of scoliosis based on 3D radiographic features. The only user interaction was to identify six landmarks per vertebra on each radiograph. The system automatically performed the 3D spine reconstruction, 3D feature extraction, and decision making. Experiments demonstrated its accuracy and consistency. This system can be an objective aid to surgeons in the task of making treatment decision for scoliosis.

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