A Novel Framework for the 3D Analysis of Spine Deformation Modes

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Abstract. Three-dimensional classification of scoliosis is important. However, analyzing large databases of 3D spine models is a difficult and time consuming task. To facilitate this task a method that automatically extracts the most important deformation modes from a set of 3D spine models is proposed. The 3D spine models are first converted into vertebrae relative positions and orientations. Then, a variability model composed of the Fréchet mean and of a generalized covariance is computed. A principal component analysis is applied to that variability model and the extracted components are converted into deformation modes. Those modes are visualized by animating a 3D spine model where the deformation strength varies (for a given mode). The proposed method was applied to a group of 307 scoliotic patients and meaningful deformation modes were successfully extracted. For example, patients' growth, double curves, simple thoracic curves and lumbar lordosis were extracted in the first four deformation modes. Moreover, the obtained deformation modes are not disconnected from conventional surgical classifications since a logistic regression confirmed that there is a statistically significant relation between King's classification and the first four principal deformation modes. The proposed method successfully extracted important deformation modes from a set of 3D spine models and can be used to refine arbitrary classes (King's or Lenke's classes, for instance), thus helping the design of new clinically relevant 3D classifications.

1. Introduction

Classification is a decisive part of the assessment of adolescent idiopathic scoliosis (AIS). The classification schemes that are currently used such as King's [1] and Lenke's [2] classifications were designed to guide the selection of fusion and instrumentation levels. Those classification systems are based on 2D measures performed on radiographs. However, spine deformations are three-dimensional and there are evidences that, by taking into account the three-dimensional nature of the deformations, sub-classes that are relevant to surgical planning could be found [3].

However, the choice of a method that takes into account the three-dimensional nature of the deformation is far from being trivial. Poncet et al. [4] proposed a classification that was based on spine torsion. Duong et al. [3] used a wavelet transform of the vertebrae centroids and a clustering method to agglomerate similar 3D spine shapes. Both methods are technically elegant and demonstrated that 3D classifications are important and possible. However, those methods are not considered to be very intuitive by physicians.

Thus, instead of the proposing yet another classification, we present a geometric method that can be used to find the most important geometric variation modes in databases of 3D spine models. These modes will indicate what varies the most from a geometric perspective in a given group, thus helping the physician in the task of analyzing large sets of 3D spine models, which is a necessary but tedious task, to define a clinically relevant 3D classification.

The next section will outline the method used to extract those modes. The information that is necessary to understand the results will be explained. However, the mathematical details of the method will not be presented (but can be found in another paper [5] about spine deformation modes). To illustrate the potential of this method, the four most important modes of variations extracted from a database of AIS patient will be presented. Then, the relationship between the extracted modes and the King's classification will be analyzed with a logistic regression. Finally, a discussion of the results and an outline of possible improvements to the method will conclude this paper.

2. Method

In order to analyze the spine deformation modes, a set of geometric descriptors have to be chosen. Then, a statistical model that is based on the chosen geometric descriptors must be computed and the principal modes of deformation can be extracted from this statistical model.

2.1. Intervertebral Rigid Transforms

The spine geometry was described using the rigid transforms that separates local coordinates systems of consecutive vertebrae. Therefore, a single spine model will have a rigid transform associated with every intervertebral space. A rigid transform is the combination of a translation and a rotation. Therefore, this geometric model takes into account not only the relative positions of the vertebrae, but also their relative orientations. The rigid transforms were expressed by a translation vector, a rotation axis and a rotation angle (see Figure 1).

These rigid transforms are computed by triangulating anatomical markers in pairs of calibrated radiographs [6] and by rigidly registering the anatomical markers of a vertebra to those of its first upper neighbour.

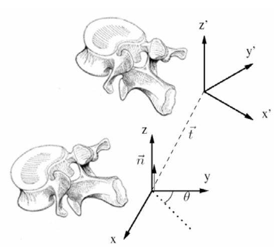

Figure 1. A rigid transform between the local coordinates systems of two consecutive vertebrae (described by a translation vector t, a rotation axis n and an angle of rotation θ)

2.2. Statistical Spine Model and Principal Deformation Modes

The extraction of the principal deformation modes from a database of spine models expressed using rigid transforms requires a statistical model. In the context of our problem a simple statistical model with only a centrality and a directional dispersion measure is enough. This statistical model would usually consist of a mean and a covariance matrix. However, computing the mean of rotations (and thus of rigid transforms) is ambiguous, because rotations cannot be added or multiplied by a scalar (they can only be composed or inverted).

However, the Fréchet mean can be used instead of the conventional definition of the mean since it is defined using the distances between the elements that we would like to average. Moreover, the computation of the Fréchet mean is simple in the case where the exponential and log maps associated with the chosen distance are known. Furthermore, it is possible to define a distance function that is invariant to left (or right) composition (once again technical details can be found in [5]).

The dispersion of the spine models around the Fréchet mean is then captured by a covariance matrix computed in the tangent space of the Fréchet mean. This measure of the dispersion has all the properties of a traditional covariance matrix. Therefore, linear operations can be performed on it. The extraction of the principal deformation modes is then very simple: it consists in computing the eigenvectors of the covariance matrix and sorting those vectors with respect to their corresponding eigenvalues.

The principal deformation modes define an orthonormal basis of the tangent space around the mean. Therefore, it is easy to reconstruct spines models by specifying the amount of deformation associated with one (or many) deformation modes. This property will be used to illustrate the deformation modes.

3. Results

3.1. Deformation Modes

A database of 307 scoliotic patients from the Sainte-Justine hospital was used to compute the principal deformation modes associated with scoliosis. The selection of the patients included in this database was based on the availability of the radiographs needed to compute 3D reconstructions of the spine.

The selection of the subjects did not take into account individual factors such as the age, sex or type of scoliotic curve. Therefore, the statistical model used to extract the principal deformation modes captured many sources of variability such as: the anatomical variability inherent to the pathology but also growth stage, posture, landmarks reconstruction error, *etc*. However, posture during data acquisition was normalized to limit its influence on the results and synthetic experiments suggested that landmarks reconstruction error was associated with a very small proportion of the observed variability.

To illustrate the different deformation modes retrieved using the proposed method, four models were reconstructed for each of the first four principal deformation modes. Those models were reconstructed with deformation strength set to -3,-1,1 and 3 times the standard deviation associated with a deformation mode. The first and second deformation modes are presented at Figure 2. The third and fourth deformation modes are illustrated at Figure 3.

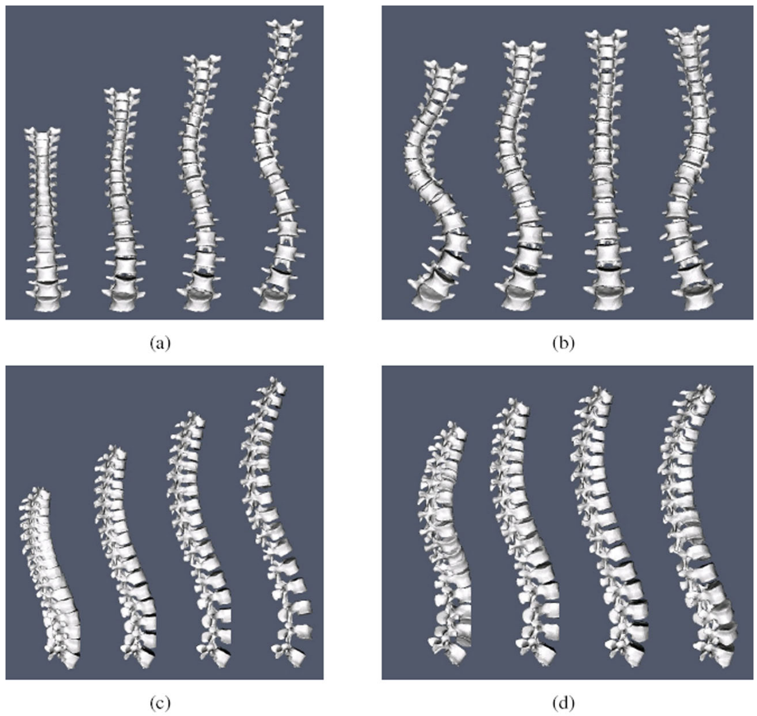

Figure 2. First principal deformation mode (reconstructions for -3,-1,1 and 3 times the standard deviation), posterior-anterior view (a) and lateral view (c). Second principal deformation mode (reconstructions for -3,-1,1 and 3 times the standard deviation), posterior-anterior view (b) and lateral view (d).

The first mode of deformation appears to be associated with the patient growth because it is mainly characterized by an elongation of the spine and it also includes mild thoracic and lumbar curves. The second principal deformation mode could be described as a double thoraco-lumbar curve. The third principal mode of deformation is a simple thoracic curve; this curve is longer than those observed in the first and second principal deformation modes. It is also interesting to note that, in addition to the curves visible on the posterior-anterior view, the second and third principal deformation modes are also associated with the development of a kyphosis on the lateral view. Finally, the fourth component is mainly associated with the development of the lumbar lordosis.

3.2. Relation with existing classification schemes

The curve patterns extracted from the principal deformation modes are connected to the pattern routinely used in different clinical classifications of scoliosis. For instance, the reconstructions built from the first principal deformation mode would be classified as a type I or III (depending on which reconstruction is evaluated) using King's classification [1], the second deformation mode would be associated to King's type I, II and III and the combination of more than one deformation modes could easily create type IV or V curves.

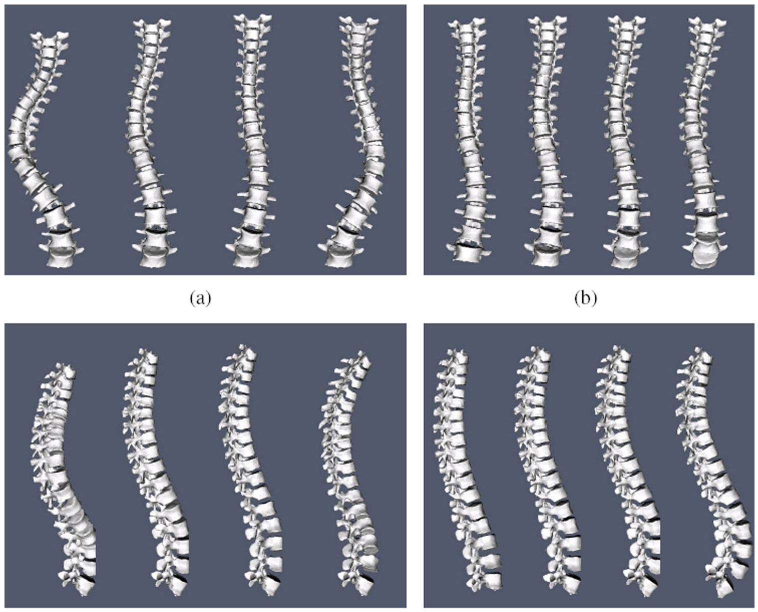

Figure 3. Third principal deformation mode (reconstructions for -3,-1,1 and 3 times the standard deviation), posterior-anterior view (a) and lateral view (c). Fourth principal deformation mode (reconstructions for -3,-1,1 and 3 times the standard deviation), posterior-anterior view (b) and lateral view (d).

	Deformation modes regression coefficients			
King's class	a_1	a_2	a_3	a_4
V	-2.33	-1.18	-8.79	10.23
IV	0.03	2.81	7.29	-
III	1.13	-2.10	-3.87	1.49
II	1.43	-1.94	-0.89	-5.84
I	-0.93	1.38	4.09	-

Table 1. Result of a logistic regression between the first four principal deformation and the King's classes

To demonstrate quantitatively that the principal modes of deformation were linked to clinically used classification, a logistic regression between the King's classes and the first four modes of deformations was performed on 33 subjects. Those subjects were randomly selected and had at least one curve with a Cobb angle of 30 degrees or more. Because of the small number of cases in this analysis, weights were used to balance the numbers of cases in each class during the regression. The results of this analysis are presented in Table 1. Statistically significant effects were found for every classes and it appeared that King's classes are usually not linked with one deformation mode but with a combination of more than one mode. For example, type V membership prediction has large coefficients associated with negative values for the third mode and for positive values of the fourth mode.

These results indicate that there is a strong connection between 2D classifications used for surgical planning and automatically extracted deformations modes. Moreover, the deformations modes are truly three-dimensional, thus frontal deformations of the spine are associated with lateral deformations.

4. Discussion and Conclusion

A method that performs an automatic extraction of the most important modes of deformation on spine models was presented. The method has strong mathematical foundations and was able to extract deformation patterns that were previously derived from surgeons' intuition and experience. Moreover, a statistical link between a more formal surgical classification system (King's classification) and the principal deformation modes was found. The proposed method can also be used to find the principal modes of deformation in more specific groups of patients, for instance, to refine classes in a 3D classification system.

One of the limitations of the proposed framework is that it analyzes inter-patients geometric variability, but it does not incorporate any temporal effect to study intra-patient geometric variability. Therefore, one interesting perspective would be to extend the method to the analysis of temporal progression of spinal deformities to find 3D progression patterns.

Acknowledgement

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